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SUSTAINABLE MOBILITY

Lightweighting:
the players, the stakes and the keys to unlocking potential gains

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With our best regards and thanks,

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This study is part of a series created in partnership with Cambridge University's Programme for Sustainability Leadership (CPSL) on topics that present investment opportunities with the potential to meaningfully affect key issues of sustainability, whether social, environmental or economic. The partnership covers two main areas, the first of which is an active research-based collaboration involving a series of joint publications over the next three years. Natixis AM analysts and Cambridge academics work together to deliver evidence-based recommendations on how to invest sustainably. The partnership's other aspect is embodied in the Investment Leaders Group, which is housed at CPSL and chaired by Natixis AM's Deputy CEO and head of Mirova responsible investing, Philippe Zaouati. The group brings together leading investment professionals to define new ways of encouraging a deeper integration of environmental and social considerations into investment decisions and increasing shareholder engagement.

Mobility is one of the eight key themes identified by Mirova for research and for SRI investment. The present study focuses on a short but ambitious list of objectives and is articulated in three parts. Firstly, the authors forge a working definition of sustainable mobility drawing on current literature in the social sciences. Secondly, on the basis of this definition, a promising area for achieving more sustainable mobility is identified: lightweighting of vehicles, particularly in the automotive industry, and potential mechanisms are offered. The third section of this report provides in depth analysis of the technologies perceived as best suited to providing energy savings through lightweighting, these being advanced high-strength steel (AHSS), aluminium, carbon fibre composites, magnesium, and several other materials.

OVERVIEW

LIGHTWEIGHT SOLUTIONS AND SUSTAINABLE MOBILITY
KEY INVESTMENT ISSUES

Why this study?

Mobility is at the heart of our development model. The railroad was the symbol of the first industrial revolution, the rise of the automobile profoundly influenced the 20th century, and the development of tourism due to civil aviation is undeniably one of the primary features of globalisation. The transport sector of the next quarter century will face further radical changes, whether via new material technologies, SMART city systems, alternative energy solutions or behavioural changes that respond to the social and environmental challenges facing our model of civilisation. This transformation is sufficiently underway for the concept of 'sustainable mobility' to have become a standard reference within both public policy and corporate strategic planning.

Despite near unanimity on the importance of sustainable mobility, there is little consensus regarding the most effective means of achieving it, let alone which solutions are most pertinent for different regions and the timeframe in which they are likely to be commercially viable or politically and socially acceptable. This study seeks to support investment professionals by clarifying some of the key features of sustainable mobility, identifying the various opportunities within a single target industry – the light duty vehicle sector - and exploring the technological, industrial and commercial implications of each solution. The report's focus on vehicle weight reduction through material substitution derives from the scale of opportunity presented by this sector, including the potential to build on major manufacturers' existing activity. The following criteria were particularly important in narrowing our focus to lightweighting in the automotive industry:

- Significant potential for environmental gain
- Relevant for all forms of propulsion (electric, thermal, etc.)
- Transverse across the whole of the transport value chain
- Current, with solutions already on the market
- Long-term potential through future innovations (eg carbon fibre, etc.)
- Relatively unexplored implications

What does sustainable mobility mean?

Talking of mobility rather than transport emphasises that movement is no longer only a means to an end but also an end in itself. Like housing or food, being mobile is a way of fully exercising our 'capabilities' as defined by Amartya Sen i.e. an individual's freedom to choose the type of life he or she will lead. For the purposes of this study, we understand the concept of *sustainable* mobility in a physical sense, as transport satisfying society's need for access and movement in an equitable manner, both on an intra and intergenerational scale (social aspect) and in a way that is compatible with the preservation of the environment (environmental aspect). Particular emphasis is placed in this report on the environmental impact of alternative technology solutions.

Why focus on vehicle weight reduction?

Mass is a crucial parameter in reducing energy demand by acting directly on the level of useful energy required to overcome the inertia and countervailing forces that prevent movement. Reducing the mass of an object you want to move (be it a car, cargo or oil in a pipeline, etc.) will reduce the energy required. Consequently, weight reduction across any mode of transport (road, rail, maritime, etc.) offers some level of energy savings. Contrary to other upstream energy efficiency measures such as engine efficiency improvement, weight reduction contributes directly to a reduction in the energy required. Furthermore, lightweighting strategies are independent of the propulsion technology employed.

Lightweight solutions can also create a virtuous circle involving the engine cylinder. The power of the engine can be reduced while achieving the same performance due to the economy in energy demand linked to weight reduction. Modifying the engine results in reduced mass for several other elements of the vehicle. With the same weight/power ratio, a lighter vehicle can do the same job with a less powerful engine and less weighty mechanical components (structure, chassis and suspension, brakes, etc.).

Finally, lightweight solutions for passenger vehicles, the fastest growing and most numerous vehicle type, appear to present a strong economic case, with a net cost of ownership to the benefit of the consumer, i.e. the fuel economy achieved through reduction in weight is above the technological price premium of the vehicle. In some cases, this surcharge is nul, as lightweighting reduces material and manufacturing costs.

Weight reduction appears to offer the greatest potential for aviation and cars. As planes must carry fuel for lift-off and to remain in the air, the influence of the unladen weight on consumption is huge. With more than 25% of the aviation industry's costs consisting of the fuel that makes their planes fly, airline companies recognized the significance of lightweight materials many decades ago. Lightweight materials, such as aluminium and composites, currently represent around 80% of components for a long-haul aircraft.

Since the 1970s, and the oil crises in particular, the automobile industry has also recognized the benefit of fuel efficiency solutions involving lighter cars and better engine performance. Indeed, it widely deployed such solutions between 1975 and 1980. However, shortly thereafter, the weight of cars increased dramatically under pressure from regulatory drivers such as pollution control (catalytic converters, particle filters, NOx traps, etc.), safety features (ABS, airbags, seatbelt tensioners, smart guiding systems), larger dimensions (passenger compartment and boot) and additional accessories such as improved acoustics, air conditioning, GPS or entertainment systems for backseat passengers, electrical equipment like adjustable seats, electric windows, etc.

In contrast to aviation and the automotive industry, the maritime, river and rail transport sectors have focused on engine performance. Maritime and rail services often transport bulk at low speeds: the net weight of goods is often greater than the unladen weight. These sectors have identified other ways of reducing their energy consumption, since, for a train, friction between the steel wheels and steel rails is minimal, while for ships, buoyancy is used as an opposing force to gravity and the hull/water interface produces little friction.

Lightweight solutions for HGVs (Heavy Goods Vehicles) are also secondary measures compared to aerodynamic improvement and rolling resistance reduction methods. Working on an HGVs weight also involves reducing the weight of its load packaging, including concentration.

For auto makers, however, fuel efficiency is only one parameter among many in vehicle design. While customers do consider fuel consumption in their buying decisions, they are also influenced by reliability, safety, comfort and aesthetics, which are typically associated with added weight. In fact, efforts to improve engine technologies and vehicle design have historically resulted in the increased power/acceleration of heavier cars, at the expense of fuel efficiency. Furthermore, attempts to market more efficient vehicles have often had limited success. In 1999, for instance, Volkswagen marketed the *Lupo 3L* as never exceeding 3l/100km (this equates to a 30% reduction in consumption in comparison to similar vehicles), yet the vehicle was removed from the Volkswagen lineup in 2005.

However, several key developments have recently reoriented the automotive industry's strategy towards fuel efficiency:

- Since the economic crisis of 2009 and pressures on household budgets, customers are more and more interested in vehicles' energy efficiency.
- Fuel efficiency standards have been formalised in many countries. Regulatory levers are now focused on reducing greenhouse gases, having previously relied on voluntary agreements with vehicle manufacturers to reduce vehicle unit consumption. In six of the world's largest regions (the United States, Canada, Europe, South Korea, Japan, Australia and China, which together represent around 50% of global traffic), greenhouse gas emission standards have been introduced: each manufacturer must keep average emissions for the fleet of vehicles sold (measured in g CO_2/km) within a given threshold

- OECD countries are also employing various tax incentives to encourage the purchase or use of low-emission vehicles

Weight reduction fits into this reorientation by reducing fuel consumption and *de facto* greenhouse gas emissions.

How can the weight of cars be reduced? Why focus on the substitution of materials?

Reductions in mass can be achieved either through new product design (architecture review, resizing, removing parts, thinning structures, integration of ribs, use of crumple zones, monocock structures, etc.) or by incorporating new materials providing more resistance per unit mass. However, while new product design plays a key role in lightweight strategies, with half of the estimated total mass reduction coming from architecture optimisation, the strategy remains heavily dependent on car manufacturers' innovation capacities. Therefore, it is not the focus of this study, which remains concerned with the substitution of newer materials for traditional steel. Steel has always been used for making cars. But in the face of regulatory pressures and fuel price increases, there are several viable alternatives available to manufacturers, who have to strike a balance between incremental cost, feasibility and the amount of weight reduction. This study examines the well-developed options for 2015-2025: advanced high-strength steel (AHSS), aluminium, carbon fibre reinforced composites (CFRC) and magnesium.
There is no question about the potential for environmental gains from new product design, i.e. via optimisation, re-dimension and elimination. However, in gauging the use of new materials, the environmental impact of these products (AHSS, aluminium, CFRC, magnesium) needs to be compensated by a significant fuel economy for these solutions to actually produce less carbon per kilometre travelled. In others words, substituting lightweight materials for steel in vehicles only becomes positive from an energy and CO_2 point of view after a certain number of kilometres, given that their production is more energy-intensive than that of steel.

We calculate that the use of high-strength steel , aluminium, magnesium and carbon fibre are environmentally paid back in Europe at 0 km, 80,000 km, 120,000 km and 170,000 km respectively, as compared to current production practices using regular steel, thus in less than the average vehicle lifespan in all cases. Also, these numbers are likely to drop over the coming years as further progress is made in recycling aluminium and carbon fibre.

We emphasise that these results are order-of-magnitude estimates in need of further improvement. As a limit of this study, we note that methodologies for optimizing recycling are still not resolved in any satisfactory manner, and that this is the focus of considerable research.

Which materials will succeed in the light-duty vehicles market?

Thanks to its attractive price, high-strength steel is set to play a significant role in lightweighting vehicles for the near term, particularly for the compact and midsize classes which together represent more than 70% of the European market (ICCT, 2011). AHSS could be used either on its own, or combined with carbon fibre reinforced composites. Between now and 2020, high-strength steel is set to represent between 15% and 20% of these vehicles' total weight.

Technological advances in aluminium and carbon fibre should also reduce barriers to their development, however, the cost of these materials, as well as that of magnesium, will limit their application to high range vehicles for the immediate future. Nevertheless, regulatory pressures and fuel prices, which are expected to become more and more binding, will oblige the industry as a whole to turn towards these materials in the medium term.

Taking each of these materials in turn, the most significant problems with aluminium are its:

- Energy and carbon-intensive production that significantly reduces environmental savings in the life cycle assessment

- High cost, also due to massive energy consumption (energy costs represent 30% of the global production cost for aluminium)

At this stage, no realistic progress in terms of R&D promises energy savings exceeding 10-20%.

Currently the only opportunities for reducing the energy and carbon intensity of aluminium production are either producing aluminium in areas with a low-carbon energy mix, or using recycled aluminium (20 times less energy to produce recycled aluminium than to manufacture new). Nonetheless, given current limits on the mechanical/lightweight performance ratio of high resistance strength steel, aluminium is set to integrate more and more in the medium term as a replacement for steel, in luxury cars as a first step, ahead of carbon fibre composites and magnesium, which are more expensive.

Magnesium offers potentially higher savings in terms of mass than aluminium. In addition, this metal raises fewer concerns regarding limited reserves or recycling. However, barriers to its development and penetration in the transport sector are substantial:

- Mechanical and physicochemical properties are not sufficient to replace steel with magnesium in all parts of the vehicle
- Magnesium currently commands twice the price of aluminium due to externalities. Outside of recycling efficiency, there are few technological levers with which to force prices down
- Production is even more energy-intensive than aluminium's; Chinese production, which relies on a high-carbon energy mix, dominates the market with an 80% share. Furthermore, magnesium production requires SF_6 (a potent GHG) as a cover gas to prevent the oxidation of molten magnesium. However, recycling could result in a more significant use of magnesium in cars

Since the 1950s, manufacturers have been using composites/plastics in their vehicles to address various mechanical performance requirements, to gain space, and for other specific uses. But specifically for the purposes of vehicle/aircraft weight reduction, we recognize only those with sufficient resistance to replace steel. At this stage, only composites reinforced with carbon fibre, known as 'carbon-fibre-reinforced-plastic' (CFRP), meet this requirement. This type of composite is almost nonexistent in currently marketed vehicle models. Only a few manufacturers in the top of the range segment have made the enormous investment this material requires.

Carbon fibre offers superior weight reduction to other substitute materials. However, the common perception is that development barriers for composite materials are numerous. These include cost, recycling, lifespan, unit repair, and a more energy-intensive production than steel. Potential solutions hinge on the following points:

- With new precursors and technological progress improving production processes, a decrease of almost 30% in the global cost of composites is expected between now and 2020
- Although it is more complex, recycling carbon fibre composites is now possible thanks to new methods of crushing and cracking carbon fibre, cutting and shaping waste recovery and an enhanced use of thermoplastic matrices
- Car manufacturers and carbon fibre producers have invested heavily in reducing the cycle time of carbon fiber production to approximate the current cycle time of the automotive industry
- Maintenance requires new skills due to difficulties in identifying flaws and the lack of established repair methods, though repairs are made in the aeronautic industry, and the progress of certain manufacturers has shown that there are no major technical difficulties, only a philosophy of adapted design and additional investment costs
- Finally, using more efficient production processes and renewable energies will allow an instant reduction in the life cycle analysis of carbon fibre composites

Although there has been real progress in this domain, the investment needed to further development remains significant. Therefore, without excluding the possibility of future large-scale production, it may more likely be a near-term solution for top of the range vehicle manufacturers with the means to address such a challenge.

Some aircraft are currently made using up to 50% carbon-fibre-reinforced-plastic. However, designing a plane takes months or even years, and requires a substantial investment, thereby rendering moot several disadvantages affecting the automobile industry, including long cycle periods and higher economic costs. Moreover, an aircraft that consumes less aviation fuel offers a compelling argument for an airline company making buying decisions. The lighter the plane is, the less fuel the company has to carry to lift it, and the less it uses doing so.

What investment opportunities are on the horizon?

Mirova's aim is to offer investors solutions that combine long-term value creation with the challenges of sustainable development. We are convinced that the development of lightweight materials could create sustainable investment opportunities in the light-duty vehicle value chain, from car manufacturers, original equipment manufacturers (OEMs), tier-one suppliers, to suppliers of materials.

Numerous lightweight investment opportunities have been identified, with the following being of particular interest:

- ➜ In the short term, AHSS is likely to play an increasingly important role in vehicle lightweighting until 2020, either alone or combined with composite fibre reinforced casing. By 2020, AHSS will probably contribute between 15% and 20% of a vehicle's total weight for a proportion of steel presumed constant. Other materials, despite a greater potential for lightweighting will be limited by their price to premium vehicles. Technological advances in AHSS depend on the expertise of steel producers and techniques of hot pressing (stamping is increasingly difficult as steel becomes thin and resistant). Thus, in the value chain of steel, the actors poised to benefit from vehicle lightweighting will be:
    - The auto manufacturers most committed to an integration of this kind of steel (at this stage, none really stands out)
    - To supply automakers, steel producers specializing in AHSS must have vast production capacity ; this constraint decreases opportunities for local steel workers and/or those with limited production capacity, however, no steel company currently specializes in AHSS
    - Companies involved in hot stamping technology (e.g. hot stamping press manufacturers), companies offering hot-formed steel parts, producers of hot stamping presses and rolling mills capable of producing various grades of high-strength steel with high formability

- ➜ In the medium term, the lightweighting potential of AHSS will prove limited compared to demands for energy efficiency. At the same time, technological advances in carbon fibre should reduce barriers to the development of this breakthrough technology and promote its large-scale integration in the automobile industry. Innovation is expected on the part of many actors throughout the value chain. These include manufacturers who rethink their entire production process and potentially adapt their business models to offer vehicles with Carbon Fibre Reinforced Plastic (CFRP) bodies and CFRP producers who reduce production costs, recycling time and maintenance requirements.

1 | Sustainable mobility and innovation: a necessary partnership

A. What is mobility? When is it sustainable?

1. Flow, transport and mobility

'Mobility' is a relatively recent concept. We used to talk about the transportation or movement of goods or people. Now, the notion of mobility has replaced those of transport, movement and traffic, and has the positive connotation of progress. Today it is highly valued, and encompasses everything associated with access to services. Some consider mobility strictly in terms of physical movement, while others see it as a clue, a revealing process similar to globalisation, gross domestic product, modernity or individualisation. This is, in fact, the main academic controversy surrounding the principle of mobility (Lussault, 2004).

Adding to this confusion: 'terms for geographical mobility, migration, mobility in space and daily mobility are used interchangeably to describe a more or less lasting change of place' (Bonvalet C., 2003). This definition is interchangeably applied to the rural exodus, commuting, touristic breaks and travellers' journeys, making it difficult to qualify, measure or improve. The large-scale transportation of oil in pipelines, or that of water in networks, is also often overlooked in discussions about transport policies.

2. Mobility as a social phenomenon

We are beginning to understand movement as a so-called 'derived' application: we do not move for the sake of moving, but to accomplish something. This new attitude requires an awareness of the social needs behind movement. Bassant (1986), for instance, believes that 'mobility in space is a completely social phenomenon, in other words, that it is never movement but always an action at the heart of social processes of operation and change'.

In recent years, mobility has become 'social and spatial, physical, virtual or potential,' according to Kaufmann (2004). Today we openly speak of vertical, horizontal, social, school, intergenerational or professional mobility to describe changes in the socio-economic positions of groups or individuals. Kaufmann (2009) bases his distinction between movement and mobility on this social aspect: 'movement in space becomes mobility when it also involves a social change'.

However, the novelty of mobility is less about new ways of moving (such as new ICT) than about its semantic use. When travel became 'mobility', it was redefined through its function of rendering human needs accessible. The very nature of mobility is a topic of debate in fact: is it a resource? A choice? A social constraint? A human right? A form of capital? Or just a means of access? The literature on the subject is abundant, given the multidimensional character of mobility.

Insert 1: What moves?

There have always been three components to the movement of social system:

- ➜ Movement of information within information systems: what used to be word of mouth conveying virtual information is now the telephone and telecommunication networks
- ➜ Mass movement involves the transport of production sources to areas of material consumption on which our societies are built: pipelines and drinking water networks bring energy and water to our civilisations, trucks and barges load cement, fruit and vegetables
- ➜ Passenger transport: international or internal to a particular system, individual or collective, public or private, commuter travel, by air, water, road or on foot, the transportation of people is diverse and includes any kind of movement involving people using any mode of transport

The most common explanation of mobility in the literature is that of accessibility, or simply access. The Victoria Transport Institute defines accessibility as 'the ability to reach desired goods, services, activities and destinations.' This definition echoes the *capabilities* approach developed by the economist and Nobel laureate Amartya Sen, whereby: 'individual well-being is not measured by utility, but by capability, namely the freedom of a person to choose the type of life he/she wants to lead' (AFD, 2008). However, definitions of mobility that involve capability open onto broader questions of social justice, which underly current attempts to define mobility as a right. Given mobility's close links to the right to life, liberty and the pursuit of well-being, basic mobility could hypothetically be guaranteed in the form of a minimum threshold for basic access. The application of a right to mobility is, in fact, already reflected in the French designation for the disabled: *'Personnes à Mobilité Réduite' (PRM)* (persons with reduced mobility).

While some see mobility as a right, others see it as capital on the same level as cultural or economic capital. Today, travelling requires skills. Technological and societal innovations have radically changed travel behaviour. Offering the right to mobility so construed is not limited to improving the accessibility of legitimate needs, but promoting 'learning about mobility and its underlying codes and culture' (Allemand, 2012).

3. Toward a definition of sustainable development

The complexity of mobility systems contributes to both the diversity of mobility indicators (quantitative and qualitative) and the variety of issues raised. Tools employed to measure the relevance of a mobility policy should at least be able to identify success or failure. However, their current shortcomings reflect the difficulties of measuring and implementing a transport policy at regional, national and global levels. Sifting through the major indicators used to assess mobility policies (OECD, EU, US EPA, etc.), we can see that evaluative criteria are designed in a variety of contexts for a range of performances and, most importantly, have no common commitment.

The conjunction of mobility and sustainability is a concept no more clear than mobility itself. The diversity of approaches towards sustainable development is due both to the complexity of human environmental impacts, and to the inclusion of social concerns. International cooperation has so far failed to produce a global consensus on sustainable mobility (Perschon, 2011). Morency (2013) cites the risk of opportunistic selection caused by the large number of indicators used (>350) and limitations on our knowledge in areas like climate change to explain how interpreting a mobility policy's positive or negative impact is clouded by the complexity of the concepts, their interpretation and the politics associated with issues of mobility.

Sustainable mobility is not a doctrine but rather a set of goals emerging from the fact that mobility is unmistakably moving away from a sustainable balance: increasing economic costs, entrenchment of social inequalities, declining air quality in urban centres, increased pressure on limited oil reserves, poor quality eco-systemic services on the part of utilities, greenhouse gas emissions, etc. And despite the absence of a universal definition for sustainable mobility, there is broad recognition of a need to 'hold the sector accountable for a certain notion of sustainability' (OCDE, 1997).

Given that the thorny issue of sustainability thus far resists a single solution despite a rapid pace of innovation, it is likely that the model we are looking for will be a combination of different extant solutions (and others still to come), and will no doubt differ according to the region of implementation. In addition, the relevance of any solution must also be assessed in terms of the time-frame needed to put it into action. Therefore no solution should be dismissed out of hand. Of course, as the leap towards a more sustainable future in terms of mobility becomes more urgent and widely recognised, certain transition solutions will lose their relevance.

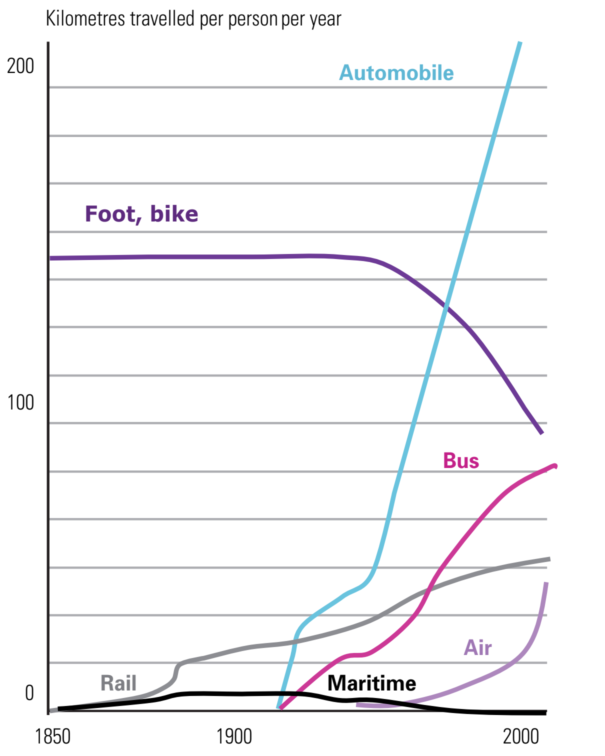
The present study, as described in greater detail below, adopts a working definition of sustainable mobility that combines a focus on equitable access to capability through movement (social concern) with quantitative improvements to performance in known areas of environmental risk, using CO_2/ passenger-kilometre as an indicator of impact. The report places particular emphasis on these latter environmental issues and the contributing role of the combustion of fossil energies on climate change and urban atmospheric pollution.

B. Innovation as a driver of sustainability

1. Current mobility models are not sustainable

The transport sector presents no exception to the exponential growth that took place during the 20th century, as highlighted in the *Limits to Growth* report (Meadows, Meadows, & Randers, 1970). On the contrary, the figures show that our world is rapidly becoming more open, free and globalised (see Figure 1).

Figure 1: Exponential growth in human mobility



Source: Mirova adapted from (Schäfer, Jacoby, & Heywood,2009)

However, despite this rosy view, current mobility patterns are not sustainable. Increased mobility needs to be decoupled from environmental pressures and social inequalities. Tracing a sustainable development model for the transport sector means allowing individuals to satisfy their travel and access needs at an intra- and inter-generational level (social aspect), in a manner compatible with preserving the environment (environmental aspect). It is clear that this compromise will be difficult to reach, as 'from an environmental point of view, the less we move around, the better, [...] from a social point of view, the most destitute need to be able to move around as much as possible and [...] from an economic point of view, exchanges need to be promoted' (Orfeuil, 2002).

The government has a key role to play in this transformation: regulatory tools, tax mechanisms, North/South cooperation and the development of public transport are all powerful tools in the search for more sustainable mobility. Other stakeholders must also contribute to the transition. The private sector, in particular, needs to adopt innovative business models that meet the demands of sustainable development. In short, this transition towards more sustainable mobility involves combining two development trends: equitable transport with low environmental impact.

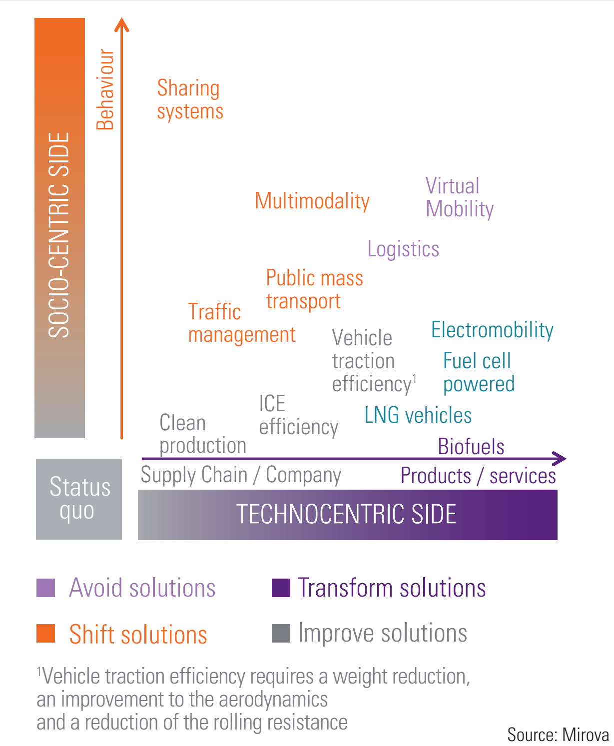
2. Towards environmentally sustainable business models of mobility

Climate change, urban atmospheric pollution and the limited supply of fossil energies are the three dominant environmental challenges to the future of mobility. The three are highly correlated in that they all largely depend on the combustion of fossil energies, making energy concerns writ large (vehicle production and mobility consumption) a determining factor in our focus here. The strategies most frequently discussed in the literature for reducing our carbon footprint contribute to addressing the above three challenges, despite slight differences. For example, the fight against local pollution focuses essentially on technologies for controlling pollutants such as lead, nitrogen oxides or particles. This strategy addresses atmospheric pollution only and has no effect on climate change.

In essence, however, environmentally sustainable strategies for mobility consist of encouraging fewer people to travel using less energy. They respond to the 4-step logic of 'Avoid-Shift-Improve-Transform' advocated by the ICCT (2012), as visually presented in Figure 2 and consisting of:

- Avoid: Reduce or avoid the need to travel
- Shift: Shift to or maintain share of more environmentally friendly modes
- Improve: Improve the energy efficiency of transportation modes and networks
- Transform: Convert vehicle fleets and fuel systems to zero emission technologies

Figure 2: Map of environmentally sustainable mobility innovations



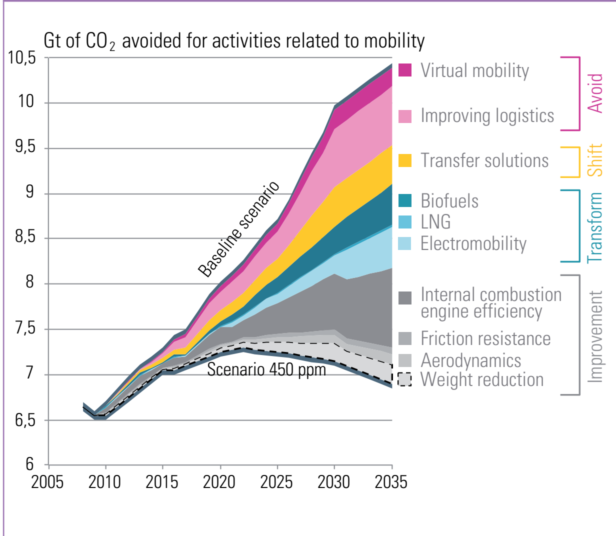
[1]Vehicle traction efficiency requires a weight reduction, an improvement to the aerodynamics and a reduction of the rolling resistance

Source: Mirova

The aim of this diagram is not to compare sustainability options, nor is it to favour some over others. On the contrary, these options are interchangeable, given that they are all motivated by the sustainability of our development. They also all have innovation as a common driver of success. Incremental initiatives (shown in grey in Figure 2) do not question our current technical choices or travel behaviours, but at the same time they are not to be disregarded.

If we look at greenhouse gas emissions, we can see that improving the energy efficiency of traditional combustion engines represents a key lever for emissions reduction. Taking a 'status quo' reference scenario and a '450 ppm' scenario that promotes the best strategic 'Avoid-Shift-Improve-Transform' practices, GHG reduction opportunities have been estimated in Figure 3.

Figure 3: Predicted contributions of sustainable mobility innovations to reducing GHG emissions



Source: Mirova adapted from IEA (2011) for emission-savings related to improvement and transformation solutions, from the ICCT (2012) for avoidance and transfer solutions and from the GeSI

Improvement solutions have a crucial role to play, representing more than a third of potential savings to be made. In the United States, Europe and China, policies to reduce CO_2 emissions for light vehicles and HGVs are vital preconditions to reducing the impact of emissions on climate change.

Each solution must be the object of a feasibility analysis that incorporates technical, economic, social and environmental criteria. This study focuses mainly on traction efficiency and, in particular, on lightweight vehicle solutions. The topic fosters innovation in the private sector, and the majority of the players' strategies in the vehicle production chain are extremely attuned to the subject.

2 | Environmentally sustainable innovation: vehicle weight reduction

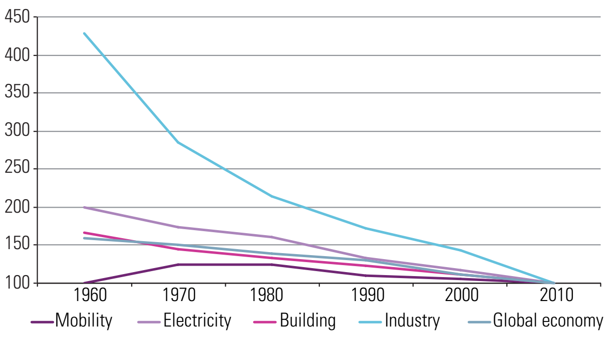
A. Energy issues in transport

1. Newly emerging energy-related transport improvements

The transport sector has always relied on conventional energy sources to power our vehicles and represents a growing percentage of our energy consumption. This growth is mainly due to road transport, and more recently, to air transport.

In terms of energy, the technological progress made in recent decades has not been sufficient to compensate for increases in mobility. Other primary energy expenditures (electricity production, industry, residential consumption, etc.) have seen annual increases in energy efficiency of more than 1% (see Figure 4). Transport is the only sector that has exhibited almost constant energy intensity (energy consumed per kilometre and per passenger) for the last fifty years (Schäfer, Jacoby, & Heywood, 2009). This can be explained by increases in the number of passenger vehicles per household due to lower fuel cost per vehicle km, and demand for ever more powerful engines that become increasingly heavy due to increases in size, added features (air conditioning, etc.) and safety requirements.

Figure 4: Comparative energy intensity for primary areas of expenditure (base 100 in 2010)

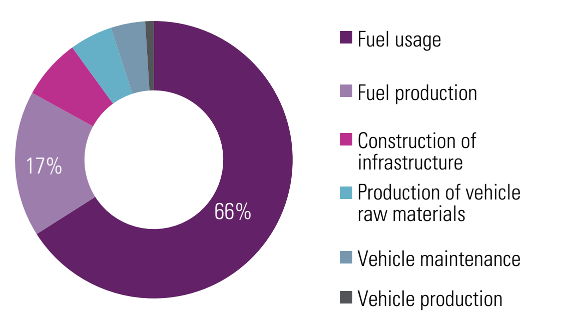


Source: Mirova according to The Oil Drum (2009) for the energy efficiency of GDP (global economy), (Ademe, 2008) for industry and buildings (within Europe), (Jancovici, 2013)for electricity (within Europe) and (Schäfer, Jacoby, & Heywood, 2009) for mobility

2. Global transport energy consumption

We tend to focus on the use phase and not the energy production phase or end-of-life disposal of vehicles' disposal, which are often energy demanding as well. This is hardly surprising, as the energy required for fuel is actually burnt, and currently represents 2/3 of the total energy in the transport value chain (see Figure 5). Consequently, we here employ a Life Cycle Analysis (LCA) framework.

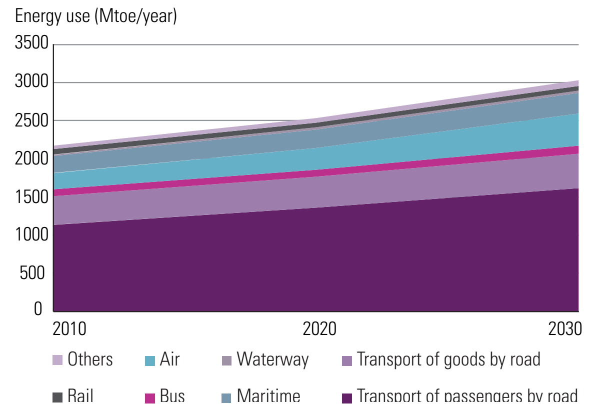
Figure 5: Energy use across the life cycle of a mode of transport



Source: Mirova adapted from (Tolley & Turton, 1995)

The bulk of the energy consumed by transporting passengers and goods relates to road (cars, buses, HGVs, etc.), air, maritime and, to a lesser extent, rail transport (see Figure 6).

Figure 6: Global energy consumption per mode of transport



Source: Mirova adapted from (WEF, 2011), baseline WEF scenario comparable to IEA scenario

Over the past few decades, road transport has been almost singlehandedly responsible for growth in global energy demand coming from the transport sector, and this is set to continue with emerging countries contributing to growth due to a car ownership rate that is steadily increasing. A growing share in total energy demand also comes from the air sector, however. The air transport industry represents a significant portion of energy consumption linked to high speed. Fuel is the second largest expense for this industry, at around 20–30% of total costs, depending on oil prices.

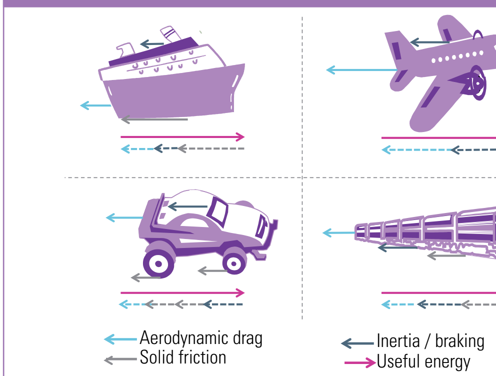
3. Overcoming the force of inertia and friction

Optimising existing improvement solutions is an important contributor to reducing the transport sector's environmental carbon footprint overall. The vehicles we use, regardless of their traction, need useful energy to overcome three types of force that oppose movement:

- Inertia dictates that to speed up or slow down requires energy released as heat (air, road, brakes, etc.)
- Aerodynamic friction, produced by the collision of air molecules with a moving vehicle,rapidly multiplies as speed increases (aerodynamics is the science that analyses airflow to reduce aerodynamic drag)
- Friction with the support (e.g. ground, water or tracks depending on the type of movement)

The balance of energy delivered by the engine is what allows the vehicle to move.

Figure 7: Forces associated with a vehicle's movement



Source: Mirova

As an order of magnitude, the energy efficiency of transport systems is around 10–25%, depending on the speed, engine performance and energy source, etc.

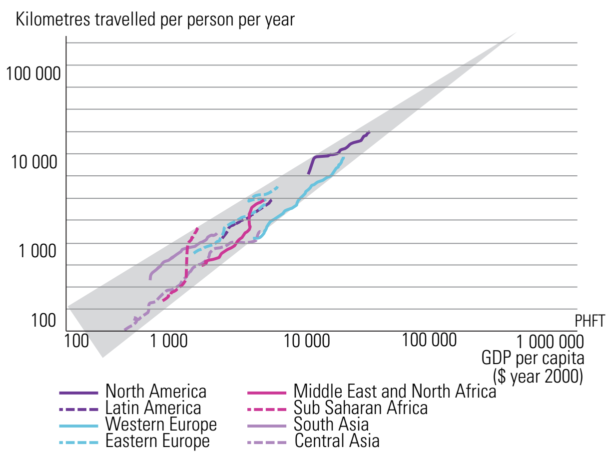
Parameters available for reducing overall energy consumption are the mass, speed and technical quality of the vehicle.

4. Difficult to decrease speed

a. People want to travel faster

Acceleration and speed are two significant parameters of energy demand. Decreasing speed represents an easy and profitable lever for energy reduction. While the development of slower transport modes is one obvious response to the energy crisis, it goes against observed trends and future estimations. Schäfer et al. (2009) have credibly demonstrated unavoidable trends in favour of quicker modes of transport. For one thing, there is an extremely high correlation between mobility and economic development (Schäfer, Jacoby, & Heywood, 2009). Travel volumes are increasing in keeping with our economic power. This is applicable to all contexts in our civilisations, whether economic, political or social. Neither energy price variations nor the various economic crises have altered the strength of this correlation. With increasing economic power, transport modes have become faster and go further. The transport sector has benefited from a relatively stable transport budget for years,[1] and societies have adopted faster modes of transport: from pedestrians using scooters and public transport in the poorest countries, to cars, planes and high-speed rail travel in the richest.

Figure 8: Mobility by geographic area mapped to economic development (1950–2005)



Source: Mirova adapted from (Schäfer, Jacoby, & Heywood, 2009)

The air and road sectors (fast modes of transport) have thus increased their penetration in our societies, much to the detriment of the rail, inland navigation and maritime sectors. The air and road sectors have better responded to the increasing need for speed, flexibility and comfort that passengers seek in our globalised society.

b. A similar trend for freight

Transport needs to achieve a compromise between speed and energy costs. Low levels of consumption correspond to slow transport modes, in line with bulk transport, which carries significant quantities of goods. In this case, the energy/speed compromise leans towards energy rather than speed. These modes of transport will be favoured when the delivery/arrival date is less important than the energy bill. High consumption levels correspond to fast transport, employed in situations where travel time takes precedence over energy costs. Today, various transport modes coexist around this energy/speed balance. Air, rail, road and sea transport are complementary modes of transport with very few potential substitutes in the context of our current travel habits.

In addition, the balance among these modes is thrown by the extreme flexibility of road transport which has made it so popular, as highlighted by infrastructure built around trading hubs underserved by rail and river transport modes. Also contributing to inertia, the long life cycle of transport equipment as well as high investment costs do not favour renewal. Substitutions among these modes correspond to the avoidance solutions above and will represent only around 10% of CO_2 savings (energy) between now and 2035. Long-distance freight and public transport offer sustainable substitution opportunities, which will become more attractive with rising energy prices (for freight, road, rail or river transport).

c. Speed is an integral part of the service provided

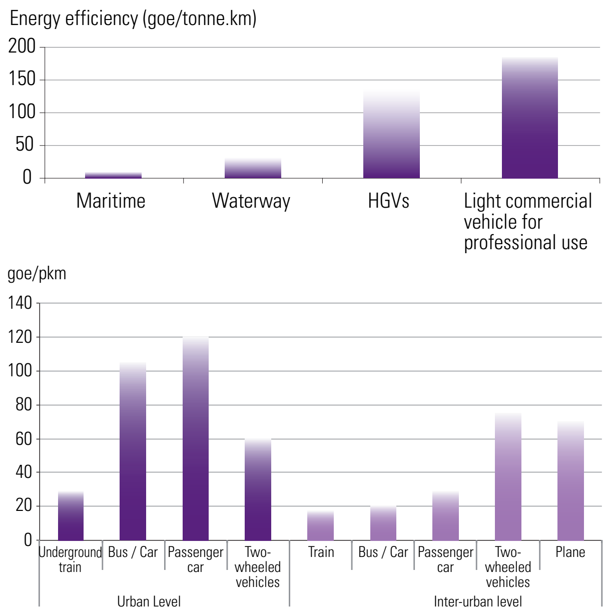
Speed is also an integral part of the service provided by transport. In passenger transport, the service provided is the transport of a person over a certain distance and time period. In freight transport, the service provided relates to the transport of goods over a certain distance and time period.

The energy cost of speed has to balance with the service provided. When comparing the energy performance of different modes of transport, we must compare the different transport modes in terms of equivalent service. However, in the literature, services provided are typically rendered comparable by standardising them. As an activity, transport is measured by passengers/kilometre for passenger transport and by tonnes/kilometre for freight transport. Thus, the consumption of a bus in passengers/kilometre is calculated by the number of passengers on board divided by consumption; cargo consumption in tonnes/kilometre is calculated by consumption divided by the weight of its load. Energy intensity therefore is measured in units of energy per passenger per kilometre and in units of energy per tonne per kilometre respectively.

The established ecological advantage of buses over cars, of cars over planes, and of sea freight over plane freight was identified using this comparative approach (Figure 9).

1. Average travel time per person is constant, regardless of how developed society or lifestyle is (urban or rural). On average, it fluctuates around 1.2 hours per day (Schäfer, Jacoby, & Heywood, 2009).

Figure 9: Global life-cycle energy efficiency for passenger and goods transport modes In goe/tkm goe/pkm

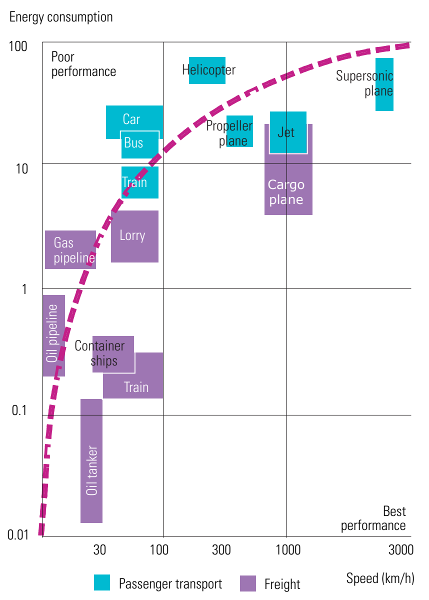


Source: Mirova adapted from (Ademe, 2008).

Note that goe = grams oil equivalent; pkm = per person and per kilometer.

Transporting a tonne of freight over a kilometre (t/km) or a passenger over the same distance (p/km) by truck, car or plane is more energy intensive than by oil pipeline, train or tram. All things being equal, this comparison is a slight misrepresentation, as the service provided is not in fact identical. When represented as distance travelled for a single unit, service fails to acknowledge speed as a parameter.
Engines are made to function at an optimum speed (and/or a maximum load) which differs according to the mode of transport. Consequently, it is difficult to compare the services provided by different modes. Chapman (1989) proposed mapping the influence of speed on energy consumption across different modes of transport (see Figure 10).

Figure 10: Modes of transport mapped to speed of movement and energy consumption



Source: Mirova adapted from (Chapman, 1989)

However, the hierarchy that distinguishes the energy performances of different modes of transport is not so clear: the energy-related profiles of a bus and a car are quite similar; likewise for air, rail and sea freight, which show similar scales of energy performance.
As a result, the energy cost of speed is rarely taken into account when comparing the performance of different ways of travelling. However, energy intensity indicators are less relevant when they fail to take speed into account as a parameter. Contrasting different modes of transport therefore requires the provision of comparable information sets, which is difficult to achieve.

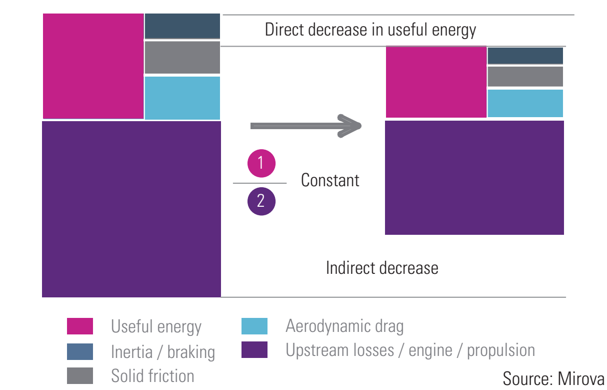
5. Weight reduction is key to improving energy efficiency

Energy efficiency is the ratio between energy useful to the travel process and total primary energy required. All transport modes focus on motorised systems in which not all energy consumed is converted into useful energy. There are losses throughout the energy value chain, primarily in the form of heat.

- Upstream, in the production of energy sources (electricity, petrol, kerosene, etc.), losses take place during the extraction and transport of crude oil and transforming it into fuel
- The engine (engine performance), where losses are mainly linked to the thermodynamic cycle, as not all heat produced can be converted into mechanical energy
- The propulsion system, specific to the type of transport (e.g. for sea transport, it is located near the propeller and for air transport, near the turbojet)

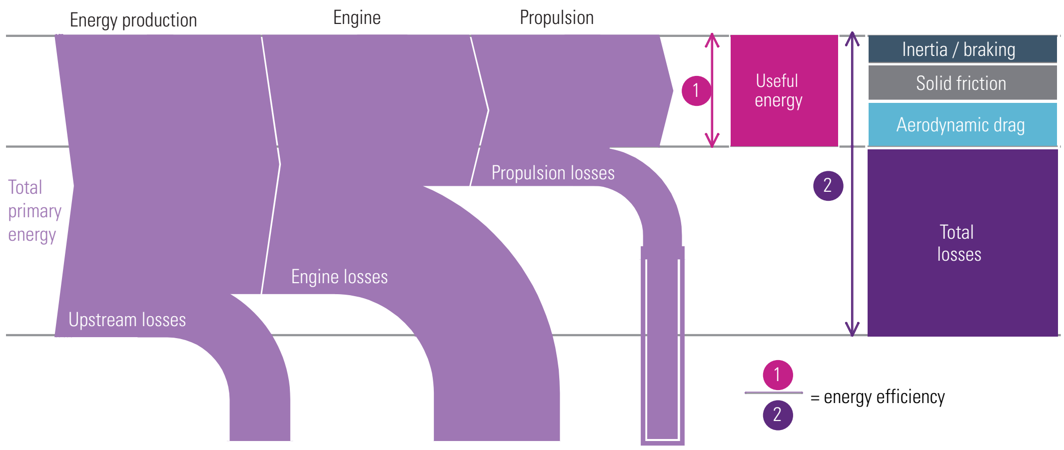
Weight is a crucial factor in reducing energy demand as it has a direct effect on the amount of total energy required. Classical physics tells us that the force needed for an object to accelerate is the product of its weight and acceleration: the heavier an object, the greater the force required. Based on this principle, reducing the weight of an object (car, cargo, oil in oil pipelines, etc.) mechanically reduces the energy consumed to achieve and maintain motion. As a result, weight reductions across all modes of transport (road, rail, sea, etc.) are intrinsically an energy-saving solution.
In other words, reducing the force of friction or weight equates to reducing the useful energy needed. Unlike methods for forestalling upstream losses in the engine or propulsion, weight reduction directly contributes to the reduction of useful energy. Required gain at this level is an indirect gain along the entire energy chain.

Figure 12: Impact of weight reduction on the global energy chain



Source: Mirova

Figure 11: Energy usage (useful + losses) by a motorised mode of transport



Source: Mirova

B. Which mode of transport is a priority in terms of weight reduction?

Numerous strategies for reducing the weight of a passenger vehicle have been identified, with the following of particular interest for lightweight vehicles:

- Optimise vehicle design by rethinking the architecture. Progress supported by simulation and testing is currently being made by revolutionising the design of vehicles and aircraft
- Resize or eliminate unnecessary components. Modifications in the design intended to slim down or eliminate elements are equally good ways of reducing the overall weight of a vehicle
- The aviation industry has already reduced the number of components on board (luggage, pillows, blankets, cups, food, headphones, etc.). Meanwhile the automobile industry is rethinking the modularity of the passenger compartment
- Electrify hydromechanics and pneumatic electronic systems (flight control actuators, landing gear and braking systems, engine architecture and electric nacelles, wiring and energy management, etc.)
- Use new materials, or find new applications and uses for known materials, instead of steel, which has been widely used in the automotive industry for a long time due to its availability, low price, durability, and its physico-chemical, mechanical, thermal and chemical properties

Weight reduction creates environmental benefits across the whole transport sector (both passengers and freight): cars, rail, sea and air. However, gains in consumption are not identical. The relationship between weight and energy is hardly a linear function. Other factors come into play such as speed, engine load, wind resistance, type of propulsion, etc. Lightweight solutions are therefore more or less efficient depending on the mode of transport. This study will focus on road and, to some extent, air transport, where potential opportunities are the most efficient and significant.

1. The rail sector is not a large enough consumer

For rail transport, energy is mainly employed in the forms of electricity and diesel. According to the International Union of Railways (2012), weight reduction is the best way to improve energy efficiency. In particular, using aluminium instead of steel for the structure of coaches and single axle trains.

New materials and new designs, such as wider trains or double-deckers, also have the potential to reduce the weight per seat by more than 35%.[2] Improvements to aerodynamics (such as the cover for open freight railcars, more compact coaches and axle covers) and brake-energy recuperation technologies (using regeneration methods in diesel trains, double-layer electrochemical supercapacitors, etc.) have proven to be the rail industry's priorities.

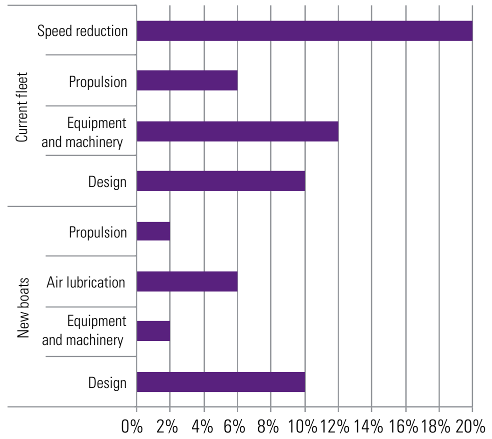
While the rail industry can benefit from making trains lighter, the overall environmental gains will be limited by rail transport's weak contribution to the carbon footprint of all transport modes combined (2% of energy from the world's transport is consumed by trains - see Figure 6).

2. The maritime industry has identified other priorities

One hindrance to using innovative technologies in the sea transport sector is the weak rotation of the floating fleet. The average lifecycle of a tanker or container is 30 to 40 years. Therefore, corrective measures to improve the extant floating fleet are more relevant. Strategies for improving energy efficiency do exist (see Figure 13), and are aimed at container ships, whose lower-energy performance, compared to tankers or bulk transport, is due to a higher speed.

2. Particularly for passenger transport as the weight of passengers is very weak in comparison to the overall weight of the train.

Figure 13: Strategies for improving the energy efficiency of maritime transport



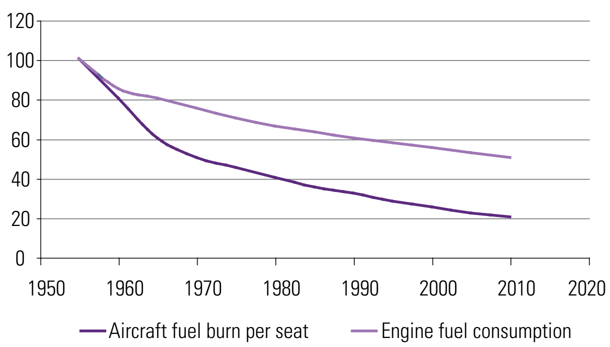
Source: Mirova adapted from (IPCC, 2008)

In addition, these strategies are geared towards energy performance and maintenance operations. Weight reduction solutions are becoming of secondary importance, as other greater energy-saving opportunities have been identified. Weight counts less in sea transport's global energy performance compared to air or land transport. Energy performance relies less on the weight of the boat than on its speed. Note, however, that the Marpol convention has added a new chapter to the annex on regulations in terms of energy efficiency, which has been in place since January 2013;[3] this highlights lightweight design as a good measure of energy efficiency.

3. The aviation industry is already working on lightweight solutions

Over the last 50 years, aircraft efficiency has increased significantly at an annual rate of 1.2-2% (WEF, 2011), which is comparable to progress in other sectors such as the chemical industry, for example (see Figure 14).

Figure 14: Energy intensity of air transport (base 100 in 1955)



Source: Mirova adapted from (IPCC, 2008)

New innovation is needed in order to continue this downward trend. Weight reduction efforts in aircraft are starting to appear within the aviation industry, such as:

- open-rotor jet engines, which improve fuel consumption by more than 25% in the long run, according to Snecma
- 'flying wing' aircraft models
- new generation dual-flow turbofans are key developments for the sector. Players foresee implementation between now and 2020

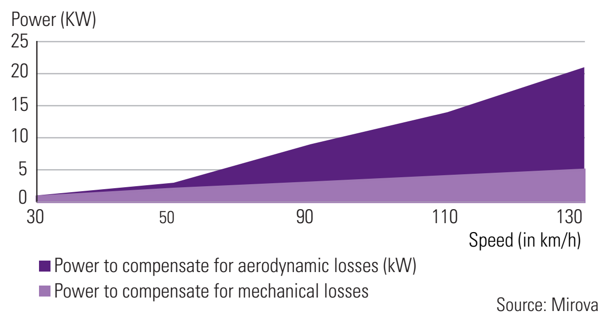
Weight reduction has managed to find its place among a variety of energy-efficient measures. The industry is working on incorporating advanced materials, such as carbon fibre composites, in the cabin and for brakes. The gain can be as much as 9% in terms of fuel economy (WEF, 2011). The new Boeing 787 has reached an energy-efficiency improvement level of 20%, by replacing steel compounds with aluminium composites.

4. Lightweight HGVs would only be relevant for urban journeys

First, note that besides friction, a vehicle consumes energy to change its velocity, i.e. speed. Speeding up, a vehicle relies on the acceleration due to mass, according to the equation $E = ½\ m\ v^2$. In urban traffic, the largest source of fuel consumption is alternating phases of acceleration/decleration, and thus results from its weight and not road surface friction.

However, aerodynamic friction increases with velocity (see Figure 15) and thus, for interurban traffic, acceleration demand is close to 0 at constant speed. Non-urban traffic therefore is less sensitive to the effects of acceleration and mainly uses energy to overcome aerodynamic drag and rolling resistance.

Figure 15: Power needed to compensate for losses (order of magnitude, road transport)



Source: Mirova

It would appear that most HGV traffic involves interurban areas. Lightweight solutions therefore are secondary measures compared to aerodynamic improvement and rolling resistance reduction methods (see Figure 15).

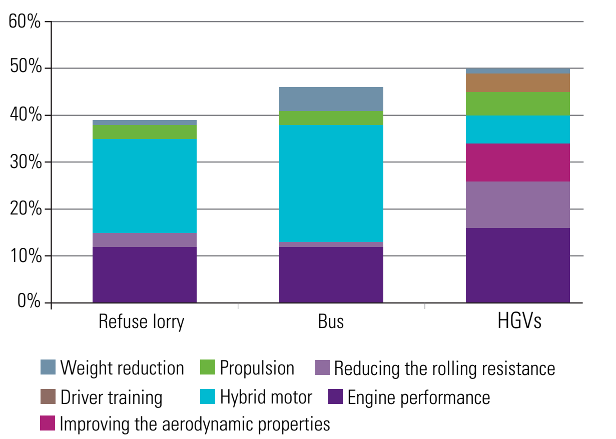
In addition, an HGV's load is often heavier than the weight of the vehicle when it is empty. Working on an HGV's weight involves also reducing the weight of its potential load. Reducing the volume/weight of the goods transported (concentration), and the volume/weight of packaging are two increasingly prioritized solutions. Finally, methods to improve HGV engines do not have to contend with reduced available space, as is the case for light vehicles.

In contrast, the relationship is reversed for HGVs in urban areas, as for buses or bin lorries. Lightweight solutions are of interest, even if, again, alternative solutions are more

3. *As of 1st January 2013, the requirements outlined in the Energy Efficiency Design index are now mandatory for all new vessels.*

promising; especially hybridisation, which is well-suited to urban areas. Potential technologies for reducing consumption between 2015 and 2020 are outlined in Figure 16.

Figure 16: Potential energy savings for HGV by strategy



Source: Mirova adapted from (Research, 2010)

5. **Passenger vehicles are the No.1 target for lightweight solutions**

A vehicle's consumption is mechanically proportional to its weight. Various studies agree that the potential figure in terms of energy reduction is around 7% for a weight reduction of 10%.

a. Weight reduction is technologically-neutral

Numerous studies on aluminium and steel, commissioned by the automobile industry, have attempted to quantify the fuel benefits linked to a reduction in weight (Forschungsgesellschaft Kraftfahrwesen mbH Aachen, 2007; Schmidt, 2004; Wohlecker, Johannaber, & Espig, 2007). Benefits vary according to numerous factors that are difficult to standardise and, while the influence of weight reduction on consumption is never trivial, factors such as the class of vehicle, type of engine or the driving cycle reference can affect it.

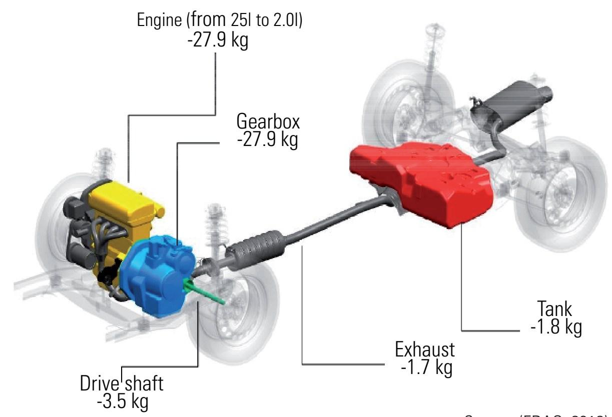
The message here is that lightweight solutions are valuable regardless of the propulsion technology employed. Lightweight solutions are transversal opportunities that cover all types of propulsion and all vehicle segments (including HGVs and commercial vehicles). Efforts in terms of lightweight solutions can be applied across the whole road transport sector.

b. The virtuous circle of mass decompounding

In addition, as a vehicle's weight increases, the weight of the tyres, wheels, suspension, brakes, steering and structure must also increase to maintain the same level of performance. As a result, weight reduction indirectly creates other lightweighting opportunities. The 'primary' weight savings therefore represent only a portion of the equation. Taking into account secondary weight-related economies could well tip the scales in favor of investment. These mass decompounding gains are not negligible: an MIT study cites publications estimating the potential secondary weight reduction for cars as ranging, on average, between 23% and 50% of the total weight reduction (Bjelkengren, 2008).

Also note that lightweight solutions create a virtuous circle involving the engine cylinder. The power of the engine can be reduced while achieving the same performance due to the energy demand economy linked to weight reduction. Modifying the engine results in reducing the mass of several elements of the vehicle, as shown below:

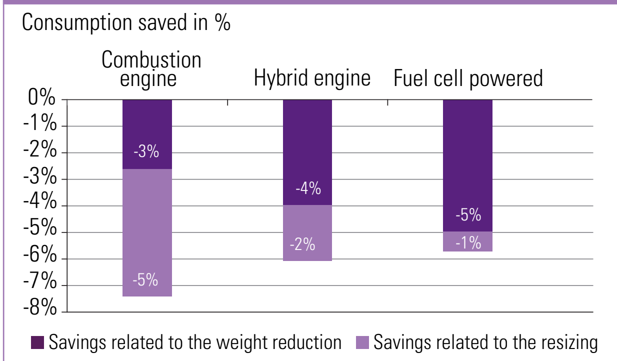
Figure 17: Example of potential mass savings due to motor downsizing



Source: (EDAG, 2012)

With the same weight/power ratio, a lighter vehicle can do the job with a less powerful engine and much less imposing mechanical components (structure, chassis and suspension, brakes, etc.). The FKA (2007) even estimates fuel economies from the type of cylinder may be more significant than those due to weight reduction directly. Reduction in mass further enables resizing of the drivetrain components, which is also a cascading process.

Figure 18: Fuel savings associated with a 10% reduction of initial weight (as %)



Source: Mirova according to (Forschungsgesellschaft Kraftfahrwesen mbH Aachen, 2007)

Weight reduction is a genuine opportunity for the transport sector to address the useful energy demand related to travel. It represents one of the main areas of improvement for an engine's energy efficiency, due to its direct effect on being able to change the size of the engine and reducing the power needed to make it work.

Each sector within the transport industry can be more energy efficient by decreasing the weight of their modes of transport. The rail and sea transport industries have nevertheless not included weight reduction as a priority in their efforts to increase energy efficiency. As a result, this study will primarily focus on the potential opportunities created in road transport (lightweight vehicles and HGVs) and aviation transport, with a heavier focus on lightweight vehicles.

C. Weight reduction challenges

1. The aviation industry's motivations

Today, lightweight materials such as aluminium and composites represent around 80% of a long-haul aircarft's components. Aircraft manufacturers started to integrate lighter materials in the 1970s (steel was rapidly displaced by aluminium at the beginning of the sector's growth and composites are progressively taking over today). Indeed, in a context of increased oil prices and pressure on ticket prices with the increasing popularity of low-cost airlines, companies in the industry are renewing their aircraft fleets, in order to achieve the following:

- Reduce fuel consumption
- Increase the fill rate per flight (by reducing the weight of the structure, airlines can carry more cargo or passengers for the same amount of fuel)

In order to achieve the ACARE (Advisory Council for Aviation Research and Innovation in Europe) CO_2 objective of a 50% reduction in CO_2/pkm[4] before 2020, fuel consumption will need to decrease by half (ACARE, 2001), and airlines need lighter aircraft. Indeed, achieving this objective will depend on numerous things: ~25% on the aircraft's structure, ~15% on the engine and ~10% on air traffic control (Rolls-Royce, 2013). The potential benefits that can be obtained through aircraft design, and more specifically lightweight solutions, are therefore very significant. This explains why the aviation industry is so keen to develop this lever.

Furthermore, it costs several billion euros to design a long-haul aircraft, so choosing lightweight materials at a higher price has a lower impact relative to the total cost of design than for a vehicle.

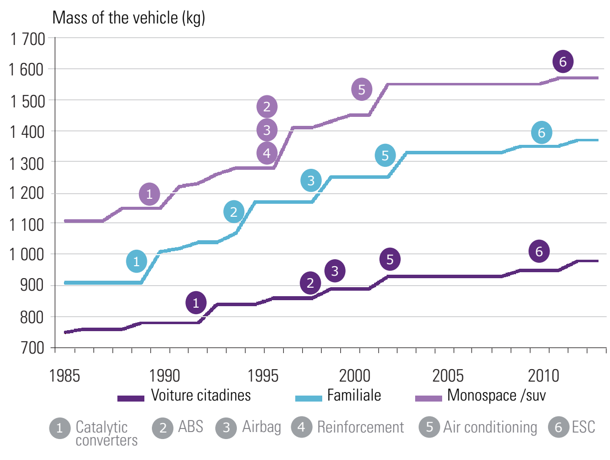
2. Reversing the trend of overloading lightweight vehicles

Although it is clear that weight reduction would decrease fuel consumption, the fact remains that cars have been getting progressively heavier for a number of years. In 1961, the average weight of a 'light' vehicle was approximately 700 kg, before it began to regularly increase to over 1,200 kg in 2011. There are numerous reasons for this trend, such as stricter safety requirements, supplementary components and an increased amount of on-board gadgets as standard across all vehicle ranges.

As suggested by Figure 19, the most recent increase is attributable to the regulatory imposition of mechanisms for pollution control (catalytic converters, particle filters, NOx traps, etc.), additional security features, adding accessories such as improved acoustics, entertainment systems for backseat passengers, electric seats and tow bars (Glennan, 2007). Larger dimensions (passenger compartment and boot/trunk) have also added to the increased weight of passenger vehicles.

4. pkm = passenger-kilometre

Figure 19: Unladen weight of light vehicles since 1985



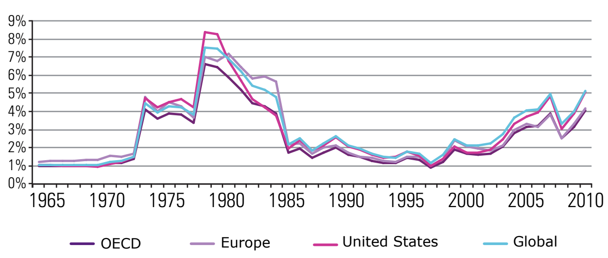
Source: Mirova adapted from (Glennan, 2007)

It is only in recent years that the tables have turned. Numerous reasons are now forcing manufacturers to take weight more seriously in the design of the vehicle models.

3. Responding to increasing pressure on oil resources

The first driver is the increase in oil prices. If we look at changes to oil price in terms of GDP per person – the 'true price' of a purchase is characterised less by its value in constant currency than by the fraction of income that must be allocated for its purchase – Figure 20 shows that this reached its historical peak during the second oil crisis in 1979.

Figure 20: Price of oil in terms of GDP per person since 1965



Source: (BP, 2013) for consumption and the price of oil and (World Bank, 2013) for GDP

After having rapidly decreased in price, energy has become 'expensive' again since 2008. This bodes well for weight reduction. Indeed, from 1975 until 1980, against the backdrop of the oil crises, US manufacturers reduced vehicle weights by nearly 25%, while keeping power for acceleration constant, resulting in a fuel efficiency increase of 57% (U.S. EPA, 2012).

Unlike previous energy crises, the price of oil has remained high, and companies are being forced to consider ways of reducing their energy consumption.

Cars and houses represent the most significant energy consumers. In addition, the transport sector is 98% dependent on fuel products, which makes it extremely vulnerable to the lack of this resource. Thus, in the latest Consumer

Reports report published in 2012, fuel economy has for the first time become an important factor in new car buying in the United States, ahead of reliability and price (Autoweek, 2012).

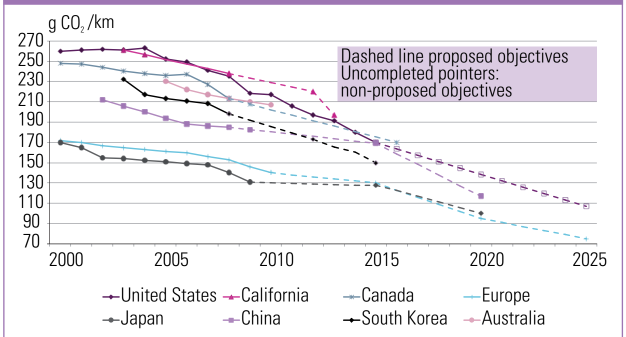
4. Responding to regulatory pressure

Weight has a direct influence on a vehicle's fuel consumption and even more effect on greenhouse gas emissions, which are responsible for climate change. International organisations have been discussing the topic for several years, and a number of projects have since aimed to cap the increase in greenhouse gas emissions. The transport sector, responsible for more than 13% of current global emissions, and road transport in particular are clearly targeted by these measures.

Voluntary agreements with car manufacturers to reduce vehicle unit consumptions[5] are now increasingly complemented by regulatory levers. Thus, in six major regions of the world, representing around 50% of world traffic, greenhouse gas emission standards for vehicles have been introduced: manufacturers are now required to limit the average emissions of the fleet sold in a given year (measured in grams CO_2/km) below a set threshold (An et al., 2007; ICCT, 2012a). Other measures in OECD countries include various tax incentives to encourage the purchase or use of low-emission vehicles (He & Bandivadekar, 2011).

Emission reduction methods vary in their scope (for lightweight vehicles only, including HGVs, etc.), driving cycle reference, total emissions, etc. An aggregate vision of regulation ambitions in terms of reducing CO_2 emissions is outlined in Figure 21.

Figure 21: Unit CO_2 emissions due to road transport: current and target emissions thresholds (adjusted to the New European Drive Cycle)



Source: Mirova adapted from (ICCT, 2012)

Manufacturers in these markets will be more inclined to lighten their vehicles to avoid the penalties incurred by exceeding the boundaries. Finally, note that some methods are indirectly more favourable to lightweight solutions. This is the case for American regulations, which are based on a vehicle's footprint and not its total weight. Given the severity of the foreseen penalties, according to a cost-benefit analysis by Ducker Worldwide (2012), weight reduction efforts work out to savings of €3.20 per kilogram using a system based on vehicle weight, and €7.60 per kilogram using a system based on carbon footprint.

5. The first agreements were signed in 1998-1999, between the European Commission and the automotive industry as represented by three manufacturing associations: (i) the ACEA (European Autmobile Manufacturers' Association), (ii) JAMA (Japan Automobile Manufacturers Association and (iii) KAMA (Korean Automobile Manufacturers' Association). Together, they aimed for an average of 140g/km in CO_2 emissions by 2008-2009 for new fleets of lightweight cars.

Insert 2: Regulatory measures are often unfavourable to weight reduction

In Europe, each manufacturer is assigned a specific objective threshold for the average CO_2 emissions of passenger vehicles sold in Europe predicated on the 'utility' of its fleet. Although long negotiations took place to determine what would be the fairest 'utility' factor, the final measure is based on the average weight of vehicles, rather than vehicle footprint, due to the greater availability of data for the former. The Commission is due to reassess this method of calculation and the reference criteria for defining objectives before 2014. Although weight is a key criterion for automobile manufacturers to remain competitive, the objective threshold method is not conducive to weight reduction. Thresholds are reviewed annually based on the range sold, which means that there is no incentive for manufacturers to lighten vehicles. Take the Daimler example; in 2009, Daimler was set a reduction objective of 137g CO_2/km by 2015, assuming the average weight remained constant at 1465kg. Suppose the group were to reduce the weight of its vehicles by an average of 100kg before that time? Their objective would become 133g CO_2/km. The weight reduction would reduce vehicle emissions by approximately 10g CO_2/km, but as the objective would be reduced from 137g CO_2/km to 133g CO_2/km, this decrease would only provide only a 6g CO_2/km gain from a regulatory point of view.

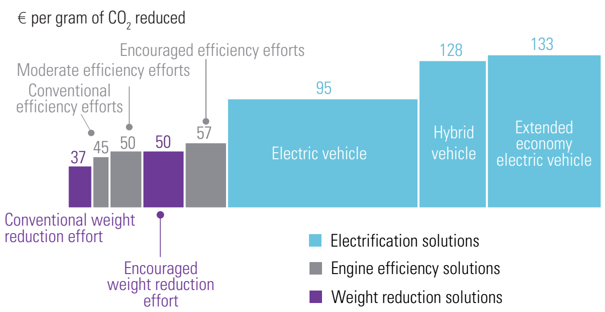
The model of penalties is not such that this prejudice against lightweighting is alleviated. Current fines stipulate that from 2012 to 2018, penalties are €5 per vehicle for the first gram of CO_2/km, €15 for the second gram, €25 for the third and €95 for anything above four grams. From 2019 onward, manfacturers will have to pay €95 for each CO_2 g/km over the target.

Moreover, note that CO_2 standards continue to ignore the energy and CO_2 embodied in the materials used to make cars.

The penalties envisaged are extremely punitive, with each excess gram costing progressively more, and are set to start at €95 in 2020. To clarify the order of magnitude, had the regulations due in 2020 been applied since 2011, manufacturers would have had to pay an average of €4,000 per vehicle sold (McKinsey & Co., 2012).

To reach their CO_2 reduction objectives, manufacturers may choose among various options, starting with measures to improve engine performance (Start & Stop, downsizing, etc.) and lightweight or electric solutions. Each option is more or less expensive according to the CO_2 economy achieved and additional investment costs incurred. McKinsey & Company (2012) has drawn out the different options, discounting the regulations issue mentioned in Insert 2, lightweight solutions are competitive with other options for reducing CO_2 emissions.

Figure 22: Marginal abatement cost for CO_2 emissions for the automobile industry (2020)



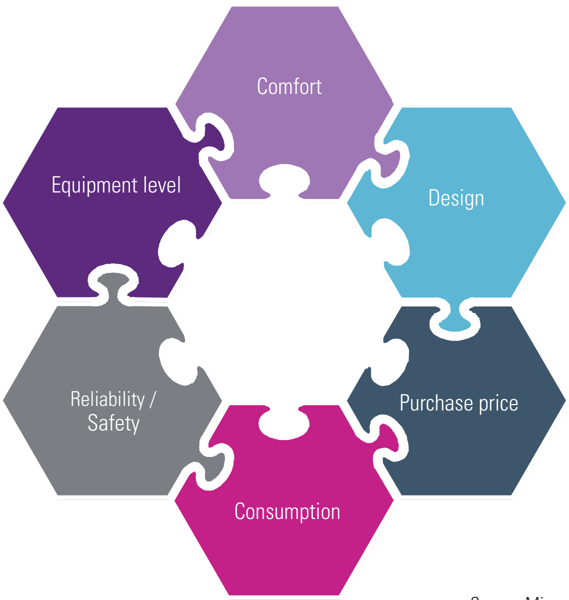
Source: Mirova according to (McKinsey & Co., 2012)

5. Reducing weight without compromising safety

The automotive industry is conscious of the need for weight reduction. According to Philippe Aumont from Faurecia, 'manufacturers have been aware of this for two or three years. Before, weight reduction was only wishful thinking on behalf of engineers and was abandoned at the drop of a hat due to deadlines, cost or services. It is now a priority, just behind cost,' (L'Usine Nouvelle, 2010). To be acceptable, lightweight solutions need to be incorporated into the vehicle design without compromising quality, comfort, safety or competitiveness. A vehicle is an investment based on numerous decision factors (see Figure 23).

Among these, fuel consumption is becoming increasingly important with the rise in energy prices. Optimum passenger safety has always been, and will always be, a priority for governments, which, over the last few years have increased requirements in terms of safety. It is important to remember that for many decades, demands for safety were largely responsible for increases in vehicle weight. Lightweight solutions will not be implemented at the expense of passenger safety.

Figure 23: The decision to invest in a mode of transport involves multiple criteria



Source: Mirova

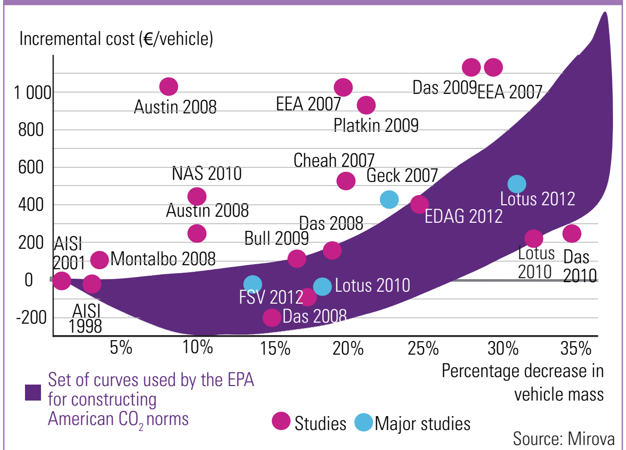
6. Reducing weight while being economically viable

Like any technological innovation, lightweight solutions must be economically viable to find a place in our transport modes. The additional costs generated are a key obstacle in the implementation of technological innovations on an industrial scale. A steep learning curve is particularly necessary both in order to limit the costs of producing new materials, and permit the manufacturer to adapt production tools to these new requirements.

Any discussion of the economic costs of lightweight solutions, this study included, must be understood as indicative only. It is indeed extremely difficult to accurately assess the costs incurred by lightweight solutions although many studies have attempted to quantify this. Figure 24 compiles the findings of studies addressing incremental costs to car manufacturers. We can see that the results differ depending on the lightweight strategy chosen, the level of effort in terms of weight reduction, but also the methodology used for calculating the incremental cost.

Variance in the results shown is primarily attributable to the different methodologies employed: which expenses should be taken into account when calculating the cost compared to a traditional solution? Should we consider R&D or the adaptation of the manufacturer's production tools? Should we also incorporate existing or future penalties on greenhouse gas emission standards? Some cost analyses will include a comprehensive study of the vehicle's parts, while others will focus on the main weight contributors (structure, drive train, etc.) or on ensuring the legitimacy of the total weight reduction, etc., although some studies question whether the materials will meet the current safety standards.

Figure 24: Incremental cost of various weight reduction solutions for vehicle manufacturers

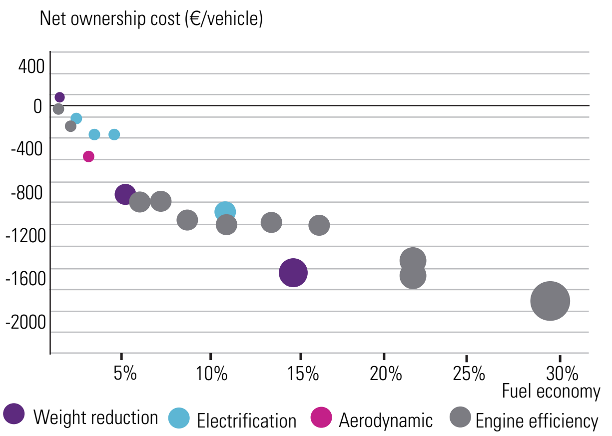


Source: Mirova

Lightweight solutions do not seem to impose significant additional costs on manufacturers, although incremental cost does increase somewhat at higher levels of weight reduction. From these analyses, it appears that a small percentage of weight can be lost without increasing the cost of a vehicle's construction. For example, according to WorldAutoSteel, it is possible to reduce the weight of a vehicle by up to 18% at no additional cost (WorldAutoSteel, 2011). In addition, weight reduction strategies often require fewer materials.

Beyond additional costs incurred by the manufacturer, it is interesting to consider the impact of weight reduction on the total cost of ownership. Again, lightweight solutions make perfect sense, with a net cost of ownership (defined as the extra technological cost paid by the consumer less fuel economy achieved through weight reduction) considerably benefitting the consumer (see Figure 25). Lightweight solutions can also be considered a viable opportunity for fuel economy, with financial gains exceeding €1,000 over the life of the vehicle. Again, these measures should be considered orders of magnitude: the sensitivity of results is low, considering the uncertainties in fuel prices and the costs generated by energy-saving solutions.

Figure 25: Net cost of ownership associated with various fuel economy solutions



Source: Mirova adapted from (Scenaria , 2012)

3 I Lightweight solutions

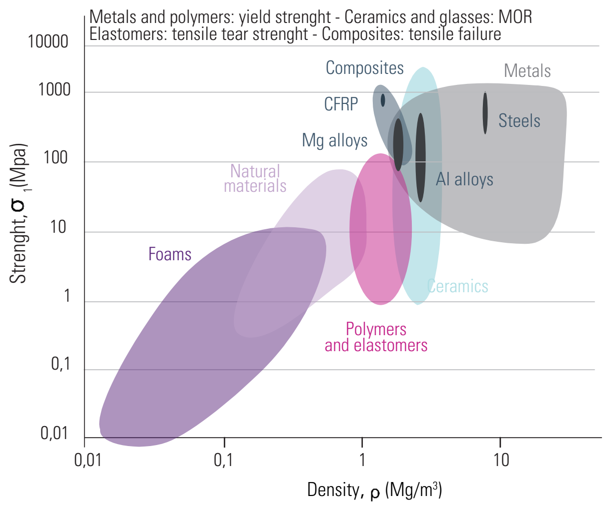
Although all lightweight strategies have their role to play in reducing weight carried (design optimisation, electronics, etc.), the one best positioned for application is the integration of lighter materials. Whether we look at AHSS, aluminium, magnesium, composite materials or titanium, the competition amongst these materials in the race towards lighter vehicles is clear and is growing apace with regulations on CO_2 emissions and the desire to reduce fuel consumption. In the remainder of this section, we will focus on each of these materials to determine its benefits, limitations and barriers to development.

Steel has always been used for making cars. It is available, cheap, robust and malleable, making it ubiquitous in the automotive industry for the chassis, body, engine parts, steering, transmission, exhaust and tyre casing, etc.

However, over the last ten years or so, and with the emergence of new comfort and security features, new materials have been introduced, including a variety of plastics. Today, there is evidence of regulatory pressure and the price of fuel is constantly increasing, forcing manufacturers to move towards lighter materials. There are several well-developed solutions available to manufacturers, who have to find a balance between incremental cost, feasibility and the amount of weight reduction.

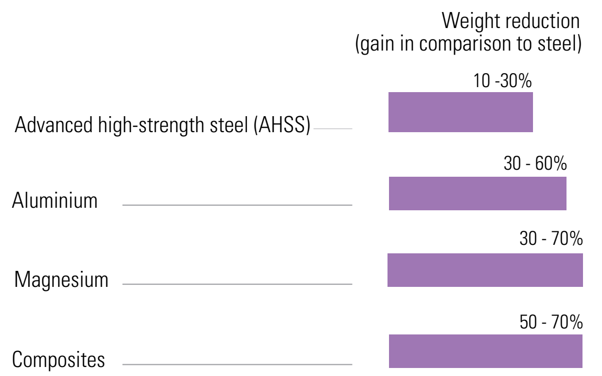
This study focuses on well-developed options for 2020-2025, examining the following lightweight materials which can be incorporated into the design of transport modes: AHSS, aluminium, magnesium and CFRP. All provide more resistance per unit mass as indicated in the Ashby plot of density and strength (see Figure 26).

Figure 26: Ashby plot of density and strength



Source: Mirova

Figure 27: New materials: comparative potential for weight reduction



Source: Mirova

A. Proving environmental relevance

Before a lightweight solution is approved as an ecologically sustainable innovation, its environmental benefit across the entire life cycle must be demonstrated. When considering the life cycle as a whole for lightweight solutions, is the environmental impact of producing innovative materials compensated for by sufficiently increased fuel economy?

The significant contribution to climate change of the transport sector demands close scrutiny of the greenhouse gas emissions produced by vehicles, both their production and their use. In this section, we will look at the screening life cycle assessment[6] (LCA) of integrating lighter materials.

6. Life cycle analysis is a recognised technique used to calculate environmental impact based on ISO 14040 and ISO 14020 standards.

The LCA approach is ideal for measuring the full environmental impact of a product or service, enabling global and efficient solutions. Primary energy consumed and greenhouse gas emissions are the environmental indicators used for the screening LCA. Other important factors for assessing environmental impact, such as recycling or pollution, are specifically noted for each material.

1. **Producing new materials is more onerous than making steel**

a. Steel

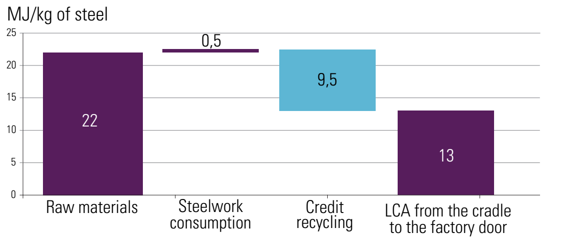
In essence, steel is produced in two different ways:

➜ In a blast furnance, via the integrated method, using iron ore and coke with carbon reduction

➜ In an electric arc furnace using scrap steel

The data in the LCA include both methods, though the electric is portrayed as the more efficient (with 5 MJ primary energy/kg). The integrated method requires more energy (~15 MJ primary energy/kg). The value used for the remainder of this study is a weighted average of these two unit consumptions, according to the total distribution of the production methods. Note that the environmental credit (in terms of energy and CO_2) linked to recycling steel is indirectly taken into account in the data used.

Figure 28: Primary energy consumption for 1kg of steel (from mining to factory door)



Source: Mirova according to (Worldsteel Association, 2011)

b. Advanced high-strengh steel (AHSS)

The use of metal alloys permits the production of special types of steel, such as AHSS. In our opinion, this modification does not consume any extra energy. The only difference between AHSS and conventional steel is the way it is pressed. Resistant steel requires more energy to stamp. However, there is little data available on the subject. Witik (2011) quantified the pressing stage for the life cycle of a steel component of a vehicle. The energy required for AHSS was double that of regular steel, given that the resistance performance of AHSS is twice as high (see Figure 37).

c. Aluminium

Overall, half of all aluminium is made from ore by electrolysis while the other half comes from scrap (remelting and refining). The aluminium used in the transport industry is mainly produced by refining scrap within a die casting process (Allwood & Cullen, 2012).

Lensink (2005) calculated a value for aluminium of 140 MJ of primary energy per kg of aluminium, based on the energy mix of Western European countries. This includes the excavation of raw materials, processing the aluminium oxide, the transportation and production of aluminium by electrolysis and the refining process route. The energy intensity of the refining route is usually estimated at 5% of the electrolysis route.

The production of primary aluminium requires large amounts of electricity (2 times more than for steel production). Thus, the carbon intensity of production depends on the energy mix of the producing country. This can range between 10-12 kg CO_2 eq/kg of aluminium in the United States and Europe, and 25 kg CO_2 eq/kg in China. China is by far the largest aluminium producer in the world, and also has the highest growth rate (Witik, 2011). Note also that PFC and SF_6, both greenhouse gases emitted during the production of aluminium, are also taken into account.

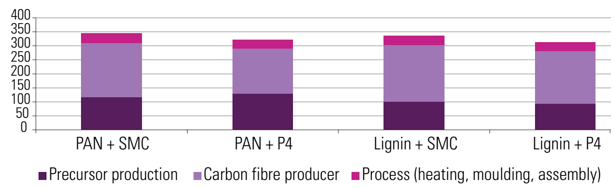
d. Magnesium

There are numerous ways of producing magnesium, all of which emit CO_2. The differences between methods depend on the type of process (thermal or electrolytic), the configuration of the oven and the carbon content of the electricity in the producer country. Performance ranges from 14 kg CO_2 eq/kg magnesium for the Magnetherm process to 43 for the Pidgeon process. With 80% of production in China, all based on the Pidgeon process, we will use this value as an average for magnesium. Note that the environmental effects of recycling have not been taken into account, as effective recycling infrastructures do not exist for magnesium (U.S. Department of Energy, 2013).

e. Carbon fibre reinforced composites (CFRC)

To model the environmental performance of carbon fibre reinforced scomposites, Das (2011) used an LCA to measure the environmental impact of a car part made of carbon fibre composites. 90% of the energy comes from the manufacturing of carbon fibre, including production of both the precursor and carbon fibres. Production of the composite, (heating, moulding and assembly) are also taken into account. Several methods of production and precursors were analysed (see Figure 29).

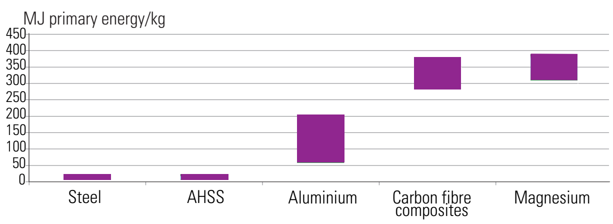
Figure 29: Energy intensity of manufacturing CFRP by process and phase



Source: Mirova according to (Das , 2011)

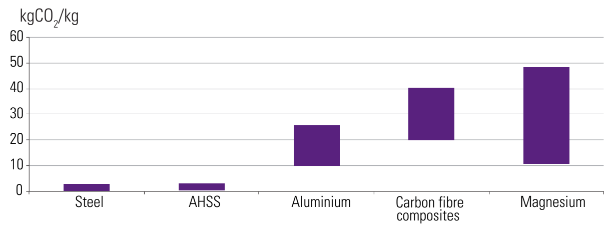
The various production methods have similar environmental performances. For the purposes of comparison, we use the figures for Sheet Moulding Compound (SMC) which is that most frequently used in the automotive industry today.

Figure 30: Comparative energy intensity of manufacturing new materials used in the automobile industry



Source: Mirova according to (Cambridge, 2010) for steel, (Cheah, 2010) for composites, (Zuliani & Reeson, 2012) for magnesium and aluminium.

Figure 31: Climate cost of manufacturing steel replacement materials for the automobile industry

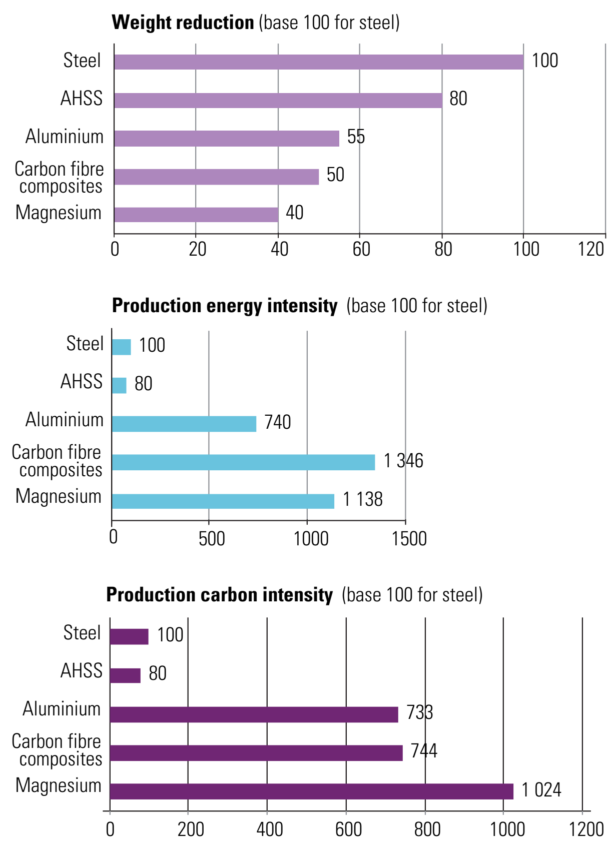


Source: Mirova according to (Cambridge, 2010) for steel, (Cheah, 2010) composites, (Zuliani & Reeson, 2012) magnesium and aluminium

The production of lightweight materials used as substitutes for steel in vehicles consumes more energy and emits more CO_2 than equivalent steel production (see Figures 30 and 31). This difference is significant for composites, aluminium and magnesium.

This additional environmental cost is less when the materials are calculated in reference to the employed mass, which is *a priori* lower than the corresponding steel mass needed for equivalent resistance. Reductions in weight achieved through the substitution of steel all come back to the concept of equivalent service. Even allowing for weight reduction, the production of alternative materials (aluminium, magnesium and composites) has a larger impact on the environment as compared to the production of steel.

Figure 32: Relative lightweighting, energy and carbon intensity for production of new materials

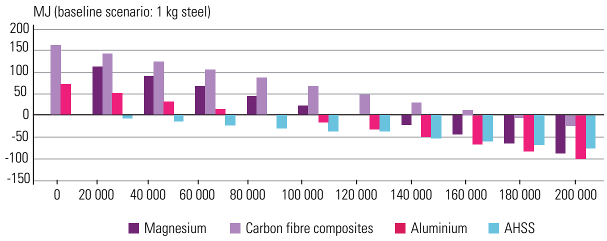


Source: Mirova

2. **What is the environmental return on investment?**

An LCA also makes it possible to identify the fuel economy generated by lightweight solutions. Many studies have attempted to quantify the fuel economy of various weight reduction strategies. Driving cycle, vehicle type, and incorporating mass decompounding are the main parameters that determine savings. The link between consumption and lightweighting is often summarised by the following statement: a 10% reduction in vehicle weight results in a decrease in consumption of 7%. Cheah (2010) confirmed this magnitude through a tripartite literature, empirical and technological validation (AVL ADVISOR™ software).Primary energy consumption and greenhouse gas emissions avoided through reductions in weight were quantified for three regions: China, the United States and Europe. The diesel / fuel distribution in car fleets, the annual average mileage and the average mass of fleets were also considered for each of these three fleets.The results are presented in the form of a return on environmental investment, that is to say, the number of miles of higher efficiency use before the additional environmental costs of producing new materials compared to steel are covered.

Figure 33: Amortization of energy investment in lightweight materials per km travelled (Europe)



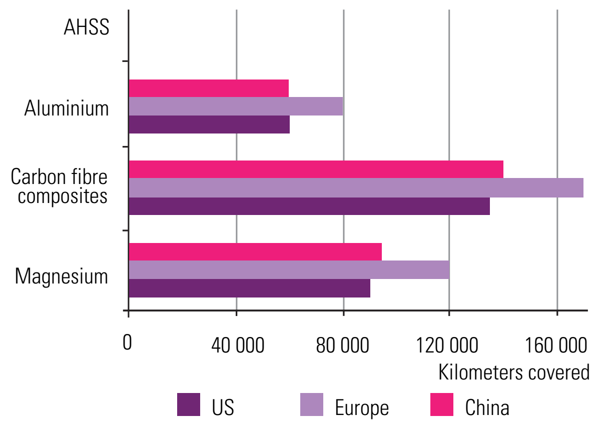
Source: Mirova

The total environmental surcharge of production compared to steel corresponds to the 0 km column. The solution is beneficial from an energy point of view when the fuel savings cancel out the additional cost of production, or when the energy cost shown in Figure 33 becomes negative. Introducing AHSS will always be a positive solution from an energy point of view, since although the production process is slightly more expensive than standard steel, less AHSS is needed to provide the same service (strength, elongation, etc.). The use of aluminium, magnesium and CFRP are paid off at 80,000 km 120,000 km and 170,000 km respectively, thus, within the average life of a vehicle. The energy intensive process of producing magnesium is quickly offset by gains associated with its low density compared to carbon fibre. Note that the literature offers a similar order of magnitude, with a return on energy investment of between 132,000 km (Duflou, De Moor, Verpoest, & W., 2009) and 162,000 km (Witik, 2011) for carbon fibre.

Sensitivity analyses were conducted for each of the main geographical regions. As average fuel consumption is higher in the USA than in Europe or China, the annual fuel economies associated are of significant interest. Moreover, this advantage is reinforced by the higher average weight of an

American car compared to its European and Chinese counterparts. In relative terms, lightweight solutions are not only more economical, they are also environmentally legitimate.

Figure 34: Km required to cancel out energy investment in lightweighting, by region

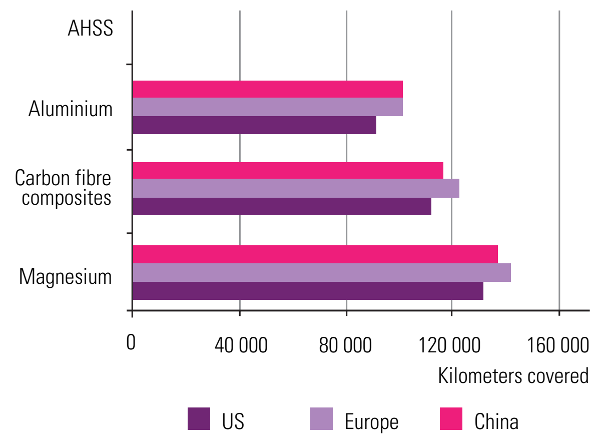


Source: Mirova

The United States once again offered the best opportunity, due to the holding period of a typical vehicle. Furthermore, the USA covers more distance per year, leading to a higher fuel consumption. Considered in terms of time, the energy payback period is between 3 and 6 years for aluminium, 5 and 10 for magnesium and is reached in 14 years for carbon fibre in Europe.

In terms of carbon, the results are naturally of the same order of magnitude (see Figure 35).

Figure 35: Km required to cancel out carbon cost of weight reduction solutions



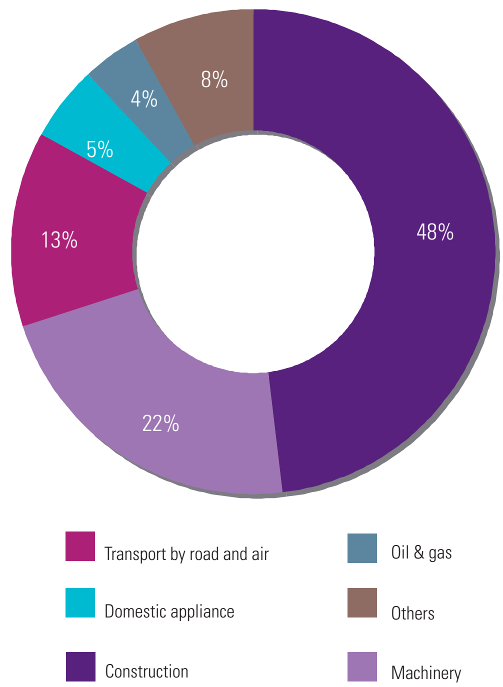
Source: Mirova

In conclusion, the use of new materials is cost-effective from both an energy and carbon perspective. Nevertheless, the return on investment is not instantaneous (except for AHSS). Carbon fibre and magnesium have payback periods of approximately a decade, therefore close to the average holding period for a vehicle. **With more efficient engines and fuel consumption averages that will continue to decline in the coming years, the environmental viability of lightweight solutions is open to question.** As proof, an earlier simulation made with the 2015 European carbon performance targets for new passenger cars revealed no environmental benefit. Reducing the environmental impact of production through increased recycling of these new materials in the coming years is needed for them to offer real environmental savings.

B. Advanced high-strength steel as a launch pad

Steel is primarily a material for ground transportation; its detrimental density has always limited its use in the aeronautic industry, which has privileged lighter materials, such as aluminium, titanium and composites. However, steel has been the basic choice for vehicle bodies due to its combination of strength, ductility and low cost. This has led to the development of a comprehensive knowledge regarding its material properties and processing, as well as how to design effective structures using steel. Nonetheless, the transport market represents only 13% of steel consumption, which is dominated by the construction of buildings.

Figure 36: Global steel consumption distribution by sector (2011)



Source: Mirova according to (World Steel Association, 2012)

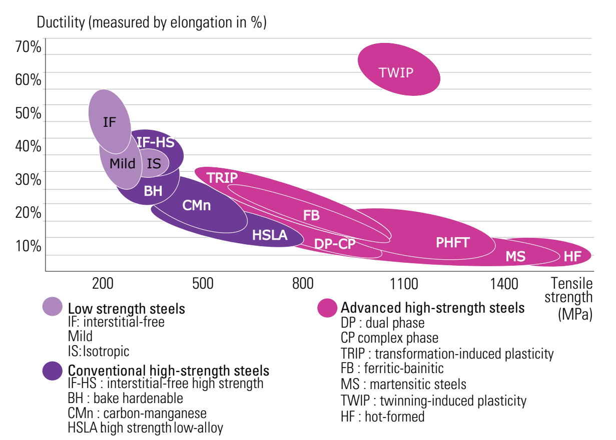
The automotive sector still represents an attractive source of growth for steelworkers, who for decades have seen their product portfolio evolve through higher value-added products. In the 1970s, steelworkers quickly understood the need of their automobile manufacturing customers to 'strengthen' their steel due to new security requirements. In 1975, the average vehicle contained approximately 4% reinforced steel. In the 1980s, the use of special steels (Interstitial Free steel, or IF) and galvanised steel became common for complex parts, in particular to fight corrosion. Then, anticipating the need for a lighter structure, the United States saw the launch of a lightweight steel body program, which has since been taken over by the World Steel Association. Other projects followed, demonstrating the ability of steel to achieve higher energy efficiency. R&D was then undertaken to 'lighten' the steel. Attempting to both strengthen and reduce weight at the same time is effectively an application of the principle lightweighting is based on: using less material that is more resistant. New steel grades available today are up to five times stronger than their predecessors, corresponding to a weight reduction of 39% compared to steel typically used in vehicles (Surma, 2013).

1. Main characteristics of AHSS

Terms often used in literature are 'conventional high-strength steel' and advanced high-strength steel'. They refer to two types of steel that behave in similar ways. Steel can be classified in different ways, depending on its carbon content, whether it is an alloy or non-alloy, strength, ductility, etc. and an international nomenclature is used to classify two different types of steel (HSS and AHSS), however, nothing allows us to clearly distinguish between the two. Steel has a continuum of common characteristics.

The difference between HSS and AHSS is somewhat arbitrary. AHSS has a different function from HSS: weight reduction, not reinforcement. As a later development, it aims to increase strength and ductility for better formability. We have chosen to follow the nomenclature used by WorldAutoSteel (Auto/Steel Partnership, 2010), which classifies different types of steel as shown in Figure 37.

Figure 37: Ashby plot of ductility and strength for steel



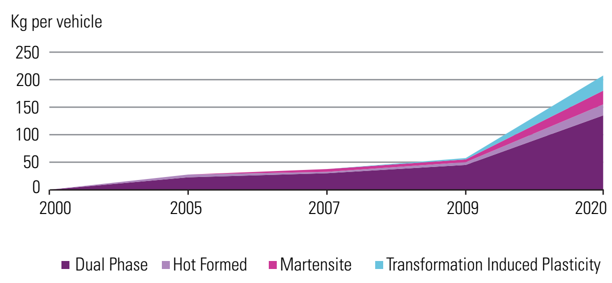
Source: Mirova according to (Auto/Steel Partnership, 2010)

Numerous types of steel exist with various properties such as strength, pliability, formability, and elasticity. We will not review the different mechanical characteristics for each of these steels. But the combination of strength with ductility is a key performance parameter for automotive applications. Indeed, in addition to weight reduction, car manufacturers also use AHSS to achieve better energy absorption in the event of impact.

2. The AHSS market

AHSS represents the fastest growing material (Ducker Worldwide, 2011) in the automotive industry. Most steelworkers are present in this market segment. Arcelor Mittal estimates a 35% penetration rate in the automotive steel market for AHSS (2013).

Figure 38: Penetration of AHSS in the automobile market



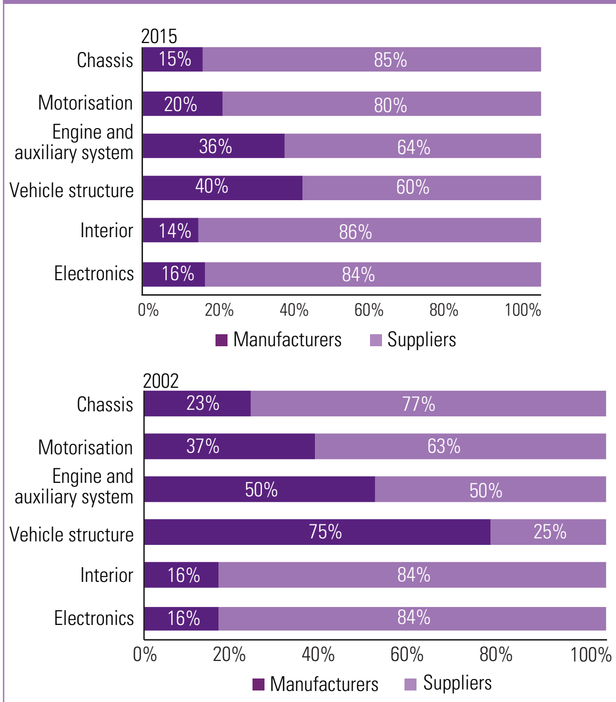
Source: Mirova

Dual Phase Steel is currently the most widely used AHSS (ferrite and martensite). This type of steel is very flexible in terms of elasticity and tensile strength, giving it a wide range of applications. It is also possible to achieve good elasticity with this steel for shock absorption, which is used for structural elements such as the doors, hood and boot. A very low elasticity, on the other hand, is ideal for critical safety components, especially for maintaining a survival space for passengers in the event of a collision.

3. Sustainable opportunities for steelworkers

Adding to the opportunities for steelworkers over the last few years, car manufacturers have started to outsource the production of car components (see Figure 39). Manufacturers have reoriented their trade to that of assembling on an international scale.

Figure 39: Outsourcing of automobile parts production



Source: Mirova according to (Synergistics, 2012)

Manufacturers have committed to a redesign of their supply chain. Steel manufacturers in particular long relied on in-house expertise for foundry, steel and stamping, which are now gradually being outsourced to steelworkers.

Suppliers, including steelworkers, have gradually become an integral part of the process of innovating the materials used. Supplier/manufacturer partnerships have emerged to provide advanced vehicle technologies.

Steelworkers producing steel amenities are present in the AHSS market, dominated by players who specialize in this field. The three geographical divisions of technological leadership and main players are as follows:

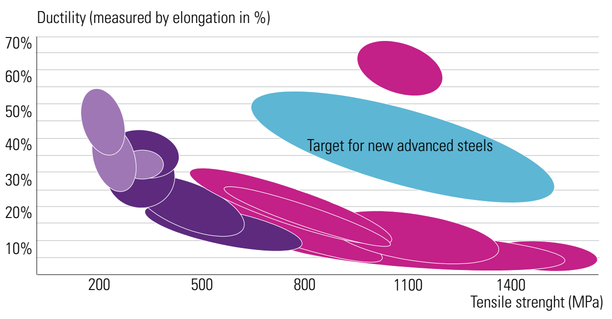
- Arcelor Mittal, Thyssen Krupp, Tata Steel and Voestalpine dominate the European market and are currently leaders in AHSS
- The North American market is experiencing growth due to increased regulation in favour of weight reduction (see Insert 3). U.S. Steel, AK Steel and Severstal share the market with other emerging companies. Strong growth is also expected in the South American market whose security requirements are starting to resemble European standards
- In the Asian market, Japanese players are those with recognised skills and expertise in AHSS. Nippon Steel & Sumitomo Metal, JFE Steel, BaoSteel and Korean Posco are well positioned there. In particular, China's car industry is set to increasingly integrate AHSS following the implementation of more stringent environmental standards

The AHSS market is likely to remain fairly concentrated. Close integration strategies between suppliers and manufacturers have appeared, squeezing local steelworkers, which in turn limits their production capacity. Only those steelworkers capable of producing quality, homogeneous AHSS in large quantities will gain market share.

4. Other opportunities in the value chain: hot-stamping

The trend of new steels has been geared towards greater and greater resistance. Advanced steels are so resistant that it is increasingly difficult to stamp them into shape with a press. We have somehow reached a limit in terms of resistance: industrial tools in the automotive industry are no longer able to stamp advanced steels. R&D on the part of steelworkers is being refocused towards better ductility at a given resistance (shown in blue in Figure 40).

Figure 40: Targets for new advanced steels (Ashby plot of ductility and strength for steels)

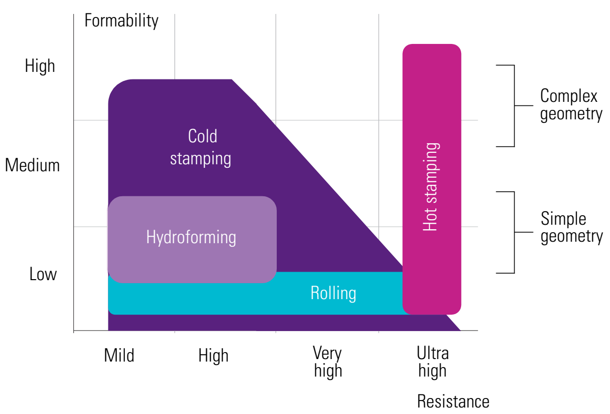


Source: Mirova according to (Synergistics, 2012)

One method was created with TWIP (Twinning-induced Plasticity steel), however, its development has been hampered by production costs, which are still too high, as well as rupture problems and difficulties welding these types of steel (Berrahmoune, 2007). Third generation steels will continue to seek applications in lightweight vehicles. Arcelor Mittal (2013) envisages the development of this steel for 2017, to arrive on the market in 2020.

Hot-formed steel is the industry's current response for overcoming the limitations of rolling tools. The automotive industry will increasingly rely on this technology. Hot stamping (around 900°C) followed by dipping the press makes it possible to create different types of high-strength steel with complex geometric structures.

Figure 41: Advantages of the hot-stamping technique



Source: Mirova according to (Gestamp, 2012)

In addition, hot-forming can offer solutions that integrate several functions, such as removing reinforcements and stages of assembly (Arcelor Mittal).

The rise of hot-formed steel will generate sustainable economic growth opportunities for those involved in the hot stamping technique. The number of extant stamping presses is low compared to forecasted growth, particularly in North America and Asia. For example, Ducker Worldwide (2012) asserts that hot stamping capabilities have tripled in North America in anticipation of ensuring 2020 growth forecasts. The development of hot-formed technology involves not only new stamping presses, but also a reduction in the cycle time of production. Production rates for hot stamping techniques are lower than for cold stamping due to the inertia of heating. Given historically low demand, the market for hot stamping was made up of highly skilled players. The major steel companies present on the AHSS market today have binding partnerships and are developing skills in this area. There are also some niche players present. The following are examples of global players who we believe will benefit from the rise of AHSS:

- Firstly, HF steel component producers such as Benteler, Gestamp and Magna
- but also, hot-stamping producers such as Andritz Group (which obtained a majority majority interest in Schuler AG in March 2013) and AP&T are benefiting from the trend

Insert 3: The role of steelworkers increasingly large in the medium-term

Source: Exchanges with Jean-Luc Thirion, General Manager Global R&D, ArcelorMittal

AHSS is a specialty steel for the automotive industry. Only steelworkers present in these specific segments of steel production can meet the challenges of the lightweight vehicle market. The steelworker markets capable of responding to this demand for lightweight vehicles are relatively concentrated on global actors who can offer high quality and consistent products across all countries.

The automotive market dominates this specialty steel sector in terms of volume, application and profitability, and push for innovation. Beyond its use in vehicles, high-strength steel also responds to weight reduction demands for trains, ships, trucks, farm equipment vehicles, construction sites and cranes.

The global car industry represents approximately 80 million tonnes/year. On average, a manufacturer uses a tonne of steel to make a car. After losses due to production faults, ~600 kg of steel is left over (a little less than 50% of a 1300 kg car). The proportion of high-strength steel within this 600 kg of steel is increasing. In 2012, this proportion was 20% vs. 5% in 2008. By 2020, high-strength steel is expected to represent 35% of all steel contained in a vehicle, or 210 kg (between 15% and 20% of the total weight of the vehicle, assuming constant total steel). Aluminium, magnesium and composite materials offer higher weight reduction potential than AHSS. However, given the cost of weight reduction, advanced steel provides a reasonable compromise between manufacturers' objectives regarding the environment and extra financial cost. According to ArcelorMittal, the compromise is in favour of high-strength steel at least until 2020 for the majority of light vehicles with a weight reduction gain of €2/kg for AHSS, €10/kg for aluminium and between €25 and €50 for carbon fibre reinforced composites.

In addition to the reduction in weight, high-strength steel improves the passive safety of vehicles and responds to increasing regulatory efforts on the matter. High-strength steel meets five-star requirements for crash tests, whilst reducing the weight of the vehicle at a moderate cost.

Whilst there are numerous benefits of AHSS, high-strength steel presents steelworkers with new challenges. First, the formability of AHSS must be increased to meet the demand of manufacturers and to make it suitable for more vehicle parts. Today, only 2/3 of vehicle parts can potentially be made using AHSS. The technical challenge of increasing the fit between AHSS and the automobile market reflects this point, and not the issue of increasing resistance, which can already reach 1900 MPa (megapascals). Moreover, steelworkers must also renew the fleet of equipment, with new mills capable of pressing finer and more layers of steel. Thus, in the medium term, advanced high-strength steel should have an increasing role to play in the manufacturing of most vehicles, either alone or combined with carbon-fibre reinforced composites. Aluminium is currently used for high-end vehicles, while carbon fibre is better suited for small-scale production.

C. Aluminium for 2020

1. Description and production

a. From bauxite to aluminium oxide…

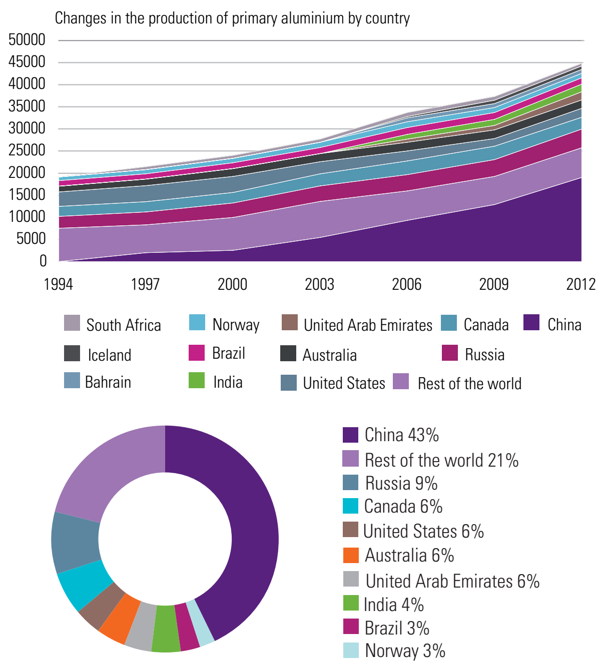
The earth's crust contains 8% aluminium and 15% aluminium oxide (Al_2O_3). Present in clays and shales, aluminium oxide is most commonly recovered from bauxite. Aluminium oxide, or alumina, is obtained through the Bayer process, which removes impurities in the bauxite ore by separating the alumina from the iron oxides. The method exploits the solubility of alumina in a basic medium (soda-based, NaOH) in contrast to the impurities (iron, etc.), which are insoluble. Using this process, it takes about 2.5 tonnes of bauxite, 7 tonnes of water, 105 kg of lime, 110 kg of soda and 200 kWh of energy to produce 1 tonne of Al_2O_3. Nearly 90% of aluminium oxide is used to make primary aluminium, with the other 10% serving a broad array of applications such as refractory materials, water treatment, paper industry, catalysts, abrasives, etc.[7]

b. From aluminium to primary aluminium…

Primary aluminium is obtained through electrolysis of Al_2O_3 in molten salt. To lower the melting point of aluminium oxide from 2040°C to 960°C, alumina is immersed in an electrolytic bath with several cryolite additives (AlF_3+NaF). During electrolysis, reactions occur between the cathode (the aluminium oxide) and the anode (CO_2). Using this process requires 1.9 tonnes Al_2O_3, 430 kg of water, 30 kg of fluorinated products and between 13,000 and 15,000 kWh of energy to produce 1 tonne of primary aluminium.

In 2012, 45 million tonnes of primary aluminium were made. Since 2000, production in China has multiplied almost tenfold, from 2 million to 19 million tonnes in 2012 (USGS, 2013).

Figure 42: Aluminium production by country



Source: Mirova according to (USGS, 2013)

7. http://www.societechimiquedefrance.fr/extras/donnees/metaux/alum/texalu.htm#Alumines

In Europe, the main producer countries are: Germanzy (405,000 tonnes), Spain (365,000 tonnes), France (334,000 tonnes) and the Netherlands (300,000 tonnes).

c. Secondary aluminium

Secondary aluminium corresponds to the recycling of aluminium. It is produced using aluminium scrap recovered either from manufacturing errors and cuttings or end-of-life objects (vehicles, packaging, etc.). Half of the aluminium currently produced is made from ore by electrolysis, while the other half comes from scrap (remelting and refining). In 2012, 42% of recycled aluminium came from the transport sector, 28% from packaging, 11% from electrical and mechanical equipment and 8% from buildings. Of a production totalling around 956 million tonnes between 1888 and 2010, 728 million are still in use today (Vignes, 2013).

2. Uses of aluminium for mobility

The transport sector is the largest consumer of primary aluminium (34% in 2012). The aluminium alloys used differ depending on the application: 2000 series (alloyed with copper) and 7000 series have good mechanical resistance for use in the aviation and aerospace industry; A-S9U3 or A-S7U3 are used in the automobile industry alloyed with silicon (Si) and copper (Cu).

In the aviation industry, aluminium first made an appearance at the beginning of the 20th Century thanks to the Wright brothers, who made the 'Wright Flyer', the first plane to have an aluminium engine. Aluminium very quickly became a popular material for planes (79% of a B747's components in 1969, 69% of an A340 in the 90s, 70% of a B777 in 1994 and 61% of an A380 in 2007) before seeing its use progressively decline in favour of composite materials (20% of a B787 Dreamliner or A350 XWB consists of aluminium versus 50% composites).

From 1920 onwards, aluminium also became a key material in the maritime industry. Today, many high-speed hulls or superstructure liners are made from aluminium alloys from the 5000 series (aluminium and magnesium) that are resistant to marine corrosion. Since 1980, aluminium has also carved itself a role within the rail industry for the construction of tubes, trams and trains as a means of reducing costs and increasing speed.
Compared to other divisions in the mobility sector, the automotive industry is behind in the use of aluminium. Although the material was first used in a car for 1947 with Panhard's[8] Dyna model, a typical 2012 vehicle only contains around 150 kg of aluminium. At this juncture, aluminium is only used extensively by luxury car manufacturers such as Jaguar, Land Rover, Audi or Ford. However, more and more parts are now being made from aluminium: bonnets (hood), bumpers, roofs and vehicles structures.

8. A nineteenth-century manufacturer bought by Citroën in 1967, currently the property of Auverland.

3. Advantages and restrictions

As we saw in Section A above, there are no concerns regarding aluminium in terms of reserves or recycling.
The percentage of weight reduction that can be achieved by using aluminium instead of steel differs for each component: 25% for an engine block and 30–35% for body panels or frames. However, weight reduction compared to steel is no more than 50% in equivalent mechanical resistance.

For manufacturers, price seems to be the biggest obstacle; and indeed, we see that they have thus far limited the use of aluminium to high-end vehicles. The cost of producing aluminium breaks down as follows: 15% raw materials, 30% energy, 16% labour and 39% other (repayments, financial costs), so the price of energy significantly influences the overall cost. In addition, aluminium's attractiveness suffers in a life cycle analysis due to its energy-intensive production. Consequently, location of production sites is important. Indeed, aluminium makers situated in regions where energy is less expensive and the energy mix is carbon-free will be at an advantage.

Moreover, aluminium faces other obstacles to its wide-scale development: repair difficulties, lack of production processes for making mass aluminium panels available, need to develop a new design to use traditional pressing, etc. (General Motors R&D, 2010).

4. A wealth of opportunities for companies able to meet demand

At this stage, there has been no progress in terms of R&D as concerns improving life cycle analysis outcomes or even production costs. Studies on the subject foresee no price improvement until 2030 (between €7 and €8 /kg). However, given limitations on the mechanical performance/weight reduction ratio of AHSS, aluminium is set to be used more frequently in vehicle design instead of steel in the medium term, ahead of carbon fibre composites and magnesium which are both environmentally and economically more expensive. Thus, aluminium producers, along with the most advanced manufacturers in this segment, should benefit from an increasing market.

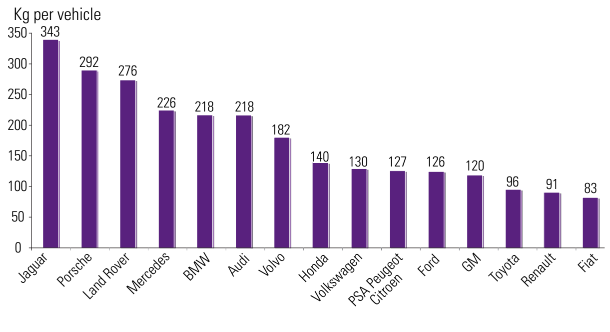
Figure 43: Main producers of primary aluminium

Primary aluminium producers (2012)	Country	Production
UC Rusal	Russia	4 170 000
Chalco	China	4 120 000
Alcoa	United States	3 740 000
Rio Tinto Alcan	Canada	3 450 000
China Power	China	2 620 000
Hydro	Norway	1 980 000
BHP Biliton	Australia	1 153 000
Dubal	Dubai	1 043 000

Source: Mirova according to (Vignes, 2013)

High-end car manufacturers are those currently using the most aluminium in their vehicles.

Figure 44: Average integration of aluminium in vehicles by maker (2012)



Source: Mirova according to (Ducker Worldwide, 2012)

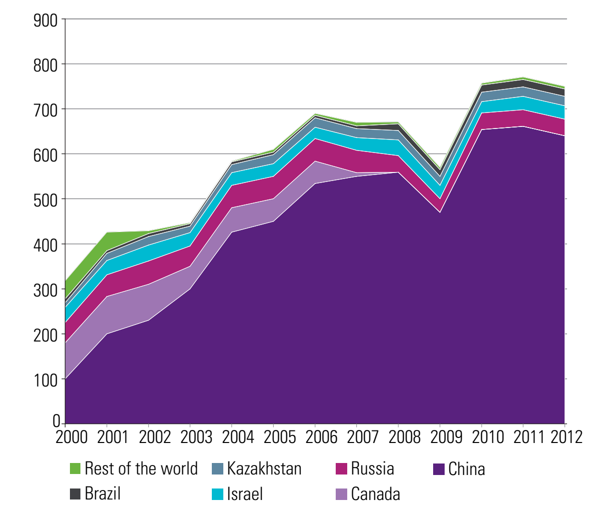
D. Magnesium has less potential

1. Description and production

The earth's crust contains 1.9% magnesium (sea water, lakes, brines, minerals). The main inorganic forms are magnesite, dolomite, carnallite and brucite. Present in many minerals, the current world production of magnesite is about 20 million tonnes per year. Magnesite can be used either directly (agricultural recycling, fillers for plastic paints, soft abrasive, etc.) or be converted into magnesium oxide (MgO). MgO is used in metallurgy and in other areas as an oxide or carbonate (agricultural recycling, glass, steel melting, ceramics, etc.).

The magnesium metal is extracted by seawater electrolysis or thermal reduction of oxydes. In 2011, around 800,000 tonnes of magnesium metal were produced i.e. ~4% of magnesite, with 81% coming from China (USGS, 2013), an increase of around 500,000 tonnes from year 2000 levels.

Figure 45: Magnesium metal production by country, 2000 to 2012



Source: Mirova according to (USGS, 2013)

The United States does not appear on the graph because production data is confidential. However, magnesium metal is present and provided by a single firm, U.S. Magnesium LLC, which has a factory in Utah and operates using brine from the Great Salt Lake. Production estimates range from 45,000 tonnes (Société Chimique de France, 2012) to 63,500 tonnes per year (USGS, 2013).
There are two main production methods (Blazy & Hermant, 2013):

- The Thermo-metallic, also called Pidgeon method using MgO (to obtain high performance magnesium alloys, easily automated, moderate investment, significant labour)
- Electrolytic method using MgCl2 (to obtain abundant magnesium metal of middling quality, initial significant investment, gaseous chlorine byproduct)

The first method is the more widely used.

Magnesium metal is particularly prized for production of alloys (40% is used in aluminium alloys, magnesium alloys), as well as refractory materials, steels and chemicals. Further applications include foundry, etc. 70% of magnesium alloys are destined for the automotive industry, especially for the manufacture of wheels (Société Chimique de France, 2012). Magnesium metal is also used in the aviation and rail industries in the form of aluminium or magnesium alloys. (Blazy & Hermant, 2013).

2. Uses for magnesium in mobility

Although Volkswagen has been using magnesium in its vehicles since the 1950s with support from Norsk Hydro (Norsk Hydro, 2007) and Dow Chemical (Bell, 2011), magnesium's place in the automotive industry currently remains relatively marginal. Of a vehicle's global mass, between 5kg and 20kg currently consists of magnesium. General Motors (General Motors, 2012) is the manufacturer that has most vocally asserted the qualities of magnesium. The company is part of the USAMP (United States Automotive Partnership), along with Chrysler and Ford, to test new possibilities for using magnesium in the automotive industry (USAMP, 2012). Ford has also invested in a lightweight plan to integrate up to 113 kg of magnesium per vehicle (CD International Enterprises, Inc., 2012). Despite the very favourable strength/weight ratio, however magnesium alloys are also used in aviation and rail industries, magnesium is still rarely substituted for steel.

3. Advantages and restrictions

Substituting aluminium, AHSS or steel with magnesium according to structural requirements, would result in weight reductions of 20–34%, 40–50% and 50–75% respectively (Zuliani & Reeson, 2012).

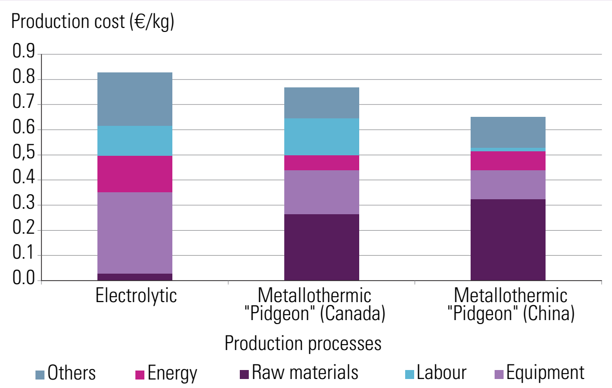
Moreover, like aluminium, magnesium is not a limited resource:

- Magnesite reserves are estimated at 12.6 billion tonnes for a global production of magnesite at approximately 20 million tonnes a year (Blazy & Hermant, 2013)
- Magnesium metal is easily recyclable (~200,000 tonnes a year of scrap magnesium from vehicles and electronic equipment no longer in use are reused alongside primary magnesium metal)

However, magnesium also faces substantial barriers:

- At the current stage of R&D development, mechanical and physicochemical properties of magnesium alloys do not permit use as a substitute for steel in all components of a vehicle
- The production cost is twice that of aluminium. By way of explanation, a brief history of magnesium production is necessary. As we saw in Section A above, from 1990 onwards, China started producing magnesium more intensively using the thermo-metallic method (Pidgeon process), developed in Canada after WWII. This production method requires modest investment and uses only magnesium oxide, but calls for a large workforce and is demanding in terms of energy consumption. It was favourable to a country like China which had large MgO reserves, and, at that time, relatively low labour costs in addition to a weak legal framework for environmental issues

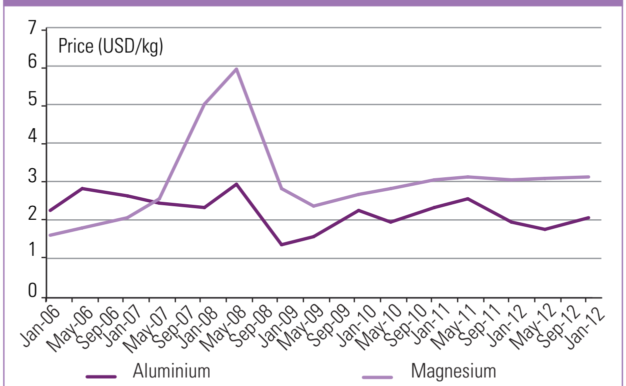
Figure 46: Cost structure for the production of primary magnesium (2012)



Source: Mirova according to (Das S. , 2008)

The increase in production on the part of China brought the market price of magnesium crashing down in less than ten years, forcing the closure of many western plants belonging to Norsk Hydro, Dow Chemical, Pechiney, Alcoa, etc.
Then, from 2005 onward, price increases in China, including: coal (+450% 2005-2011), electricity (100%), ferrosilicon (60%) and labour costs (350%) led to rising production costs reflected in the market price of magnesium (+150% between 2006 and 2008). This cost increase has caused demand for magnesium to drop in favour of aluminium.

Figure 47: Changes in the price of magnesium relative to aluminium (2006-2012)



Source: Mirova according to (InfoMine, 2013)

The low price of magnesium between 1990 and 2005 was due to very specific economic conditions in China. Today, the return to a more reasonable price of magnesium can be only be acheived by finding technological levers at the production level, or by better exploiting recyclability. In the thermo-metallic process, the price of magnesium metal production is highly correlated with that of ferrosilicon, which represents nearly 50% of global production costs. Thus, for this method of production, everything depends on exogenous factors affecting the price of ferrosilicon (steel demand, cost of electricity, etc.), which is not very promising for the future price of magnesium.

Another important difficulty to consider is that magnesium suffers from an unfavourable life-cycle analysis, making it unattractive from an environmental point of view. This is mainly due to more than 80% of magnesium production being in China, whose energy mix is high-carbon, and to energy-intensive production methods (see III.A). However, like aluminium, the geographic situation of production is a very important factor. Indeed, there is a threefold difference in global warming potential between magnesium produced in Brazil and the same metal produced in China, though both employ a thermo-metallic process.

Several sub-processes have been developed for each type of production method: Thermo-metallic (Bolzano, Pidgeon, Magneterm) and electrolytic (IG Farben, Norsk Hydro, Dow), with each process having its own global warming potential and possibilities for energy efficiency. However, at this stage, regardless of the production method, the global warming potential of magnesium is higher than that of aluminium. Furthermore, magnesium production demands SF_6 (one of the most potent GHG) as a cover gas to prevent the oxidation of molten magnesium.

4. Keys to development

From a technology perspective, companies in the value chain of magnesium are investing in R&D to find more energy-efficient and less costly processes. For example, Mintek, a South African company, has developed a heat treatment called "Mintek Thermal Magnesium Process" for making magnesium metal at a lower cost than existing thermal processes. Research is also being conducted to find methods that forgo using SF_6.
In addition, secondary magnesium consumes only 5% of the energy needed to produce primary magnesium using the thermo-metallic process, 10% if you employ electrolytic processes. Thus, in the absence of a new, less energy intensive production process, companies positioned in the recycling of magnesium, whether end-of-life or manufacturing waste, offer the best opportunities for development of the magnesium metal industry. Currently, the recycling of magnesium metal hovers around 200,000 tonnes/year (Blazy & Hermant, 2013).

5. A wealth of opportunities for companies able to meet demand

Many magnesium producers have disappeared over the last twenty years, after suffering unfair competition from China and a fall in demand since 2007. For example, Norsk Hydro's magnesium activities came to an end in 2008. Factories have also closed in Canada and Norway.

Figure 48: Main companies producing magnesium (2012)

Country	Primary magnesium production (tonnes)	Processes	Magnesium producers
China	640 000	Metal-lothermic "Pidgeon"	China Magnesium Corporation Ltd, Shanxi Wenxi Yinguang Magnesium Industry Group Co Ltd, Huozhou Hongtai Magnesium Industrial Co Ltd, Wanke Jinrun Mg Co Ltd, etc.
Russia	37 000	Electrolysis	Solikamsk Magnesium Works VSMPO-Avisma
Israel	30 000	Electrolysis	Israel Chemicals Ltd Dead Sea Magnesium»
United States	45 000	Electrolysis	US Magnesium LLC
Kazakhstan	21 000	Electrolysis	Ust-Kamenogorsk Titanium-Magnesium Combine
Brazil	16 000	Metallothermic "Bolzano"	Buschle & Lepper SA
Malaysia	5 000	Electrolysis	CVM Magnesium Sdn Bhd
Serbia	2 000	Electrolysis	MG Serbian - Bela Stena Baljevac
Ukraine	2 000	Electrolysis	Zaporozhye Titanium-Magnesium

Source: Mirova according to (Blazy & Hermant, 2013; Société Chimique de France, 2012; USGS, 2013)

However, the search for magnesium solutions does continue, with some car/space equipment/aircraft manufacturers investing in their own metallurgy, so they can develop proprietary aluminium/magnesium alloys. These include EADS Deutschland, General Motors Corporation, the Ford Motor Company, Aston Martin and Daimler Chrysler Corporation (Blazy & Hermant, 2013).

E. Are composites a material of the future for mobility?

1. Description of material

a. Definition and key characteristics

A composite is a heterogeneous material made up of at least two immiscible materials, which, once formed, possesses characteristics that the individual elements did not have. The combination or arrangement of elements is of great importance to either retain the best properties of each of them, or to produce new properties that none of the elements held separately. The properties of composite materials are therefore dependent on both the properties of the individual elements, and those that are produced from the assembly of the final material.

Composites are made up of a matrix and a reinforcement, separated by an interface (to deflect the crack in the event of impact so that it does not reach the reinforcement). The reinforcement is an important contributor to the mechanical properties, while the matrix multiplies the attributes playing a protective role of reinforcement with regards to the environment, aesthetic functions, maintaining transfer efforts, etc.

b. Types of composite per matrix

Like reinforcements, several types of matrices can be used according to the final desired functionality. Thus, composites can be divided into three main groups: organic matrix composites (OMC), ceramic matrix composites (CMC) and metal matrix composites (MMC).

Organic matrix composites

Organic matrix composites (OMC) have the greatest market presence (~90% of matrices used) and are described as either 'widely distributed' (low cost, about 95% of the OMC market) or 'high performance' (high cost, better mechanical performance). This second category has been previously used in aerospace, aviation and in motor sports. Organic matrices can be thermosetting (63% market share) or thermoplastic (37% market share).

Figure 49: Comparison of organic matrices

	Thermosetting matrix	Thermoplastic matrix
Cost	Differ according to the type of matrix	Differ according to the type of matrix
Form	Liquid	Solid
Manufacturing processes	**Simple** / Long cycle times	Complex (high temperatures required/ short cycle time
Mechanical properties	Limited shock resistance **Good thermal shock**	**Resistant to impacts**, fatigue, corrosion, cracking Limited thermal shock
Stockage	Reduced and at low temperature	**Unlimited** and at room temperature
Other impacts	Volatile Organic Compound (VOC) and solvent emissions during treatment	**No Volatile Organic Compound (VOC) emissions** during treatment
End of life	Non recyclable and non reusable	**Reusable and recyclable**

Sources: Mirova according to (Centre d'Animation Régional en Matériaux Avancés, 2004; Cetim-Cermat, 2011; Onera, 2011)

Due to their relative simplicity of design and implementation, thermosetting matrices have been far more prevalent. The following are examples of thermosetting matrices:

- ➜ Polyester (~90% thermosetting market share, easy to implement, good mechanical properties, low cost, mainly intended for 'wide distribution')
- ➜ Epoxy resins (~5% thermosetting market share, better mechanical properties than alternatives, strong adhesion capacity on carbon fibre and glass fibre (Onera, 2011), high cost)

Thermoplastic matrices provide a better repair profile, recycling opportunities (heated softening cycle and cooling solidification infinitely repeatable), and the possibility of reducing cycle times (a few minutes for thermosetting). This aspect makes thermoplastics very attractive to the automotive industry. However, these benefits entail disadvantages, including a dependence on temperature and high manufacturing costs. Several thermoplastics can be used: Polyamide (PA), Polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), Polycarbonate

(PC), Polyphenylene sulfide (PPS), Polyoxymethylene (POM), Polysulfides/Polysulfones (PSU and PPS) Polypropylene (PP) polyamide imide (PAI), polyether imide (PEI), Polyethersulfone (PES), polyetheretherketone (PEEK). So although thermosetting matrices have dominated market presence in the past, the use of thermoplastic matrices has been increasing due to better mechanical properties at high temperatures (Aucher, 2011).

Ceramic matrix composites

CMCs have ceramic fibres and matrices. This type of composite is very light and resistant to high temperatures. However, the ceramic matrix (silicon carbide, carbonated matrices, aluminium oxide) are hampered by being more expensive than organic matrices and are mainly used in the aerospace and military aircraft industries, which both require high performance materials.

Metal matrix composites

Metal matrices (such as aluminium and magnesium), which can be associated with metal or ceramic reinforcements, offer good mechanical performance. But with high costs and a complex manufacturing process to ensure cohesion between the matrix and the reinforcement, metal matrix composites are mostly confined to the aerospace industry. Matrices are not all compatible with the various reinforcements. The construction of a composite is based on a combination of matrices and reinforcements that aim to achieve the best mechanical performance and minimise weight.

c. Reinforcement

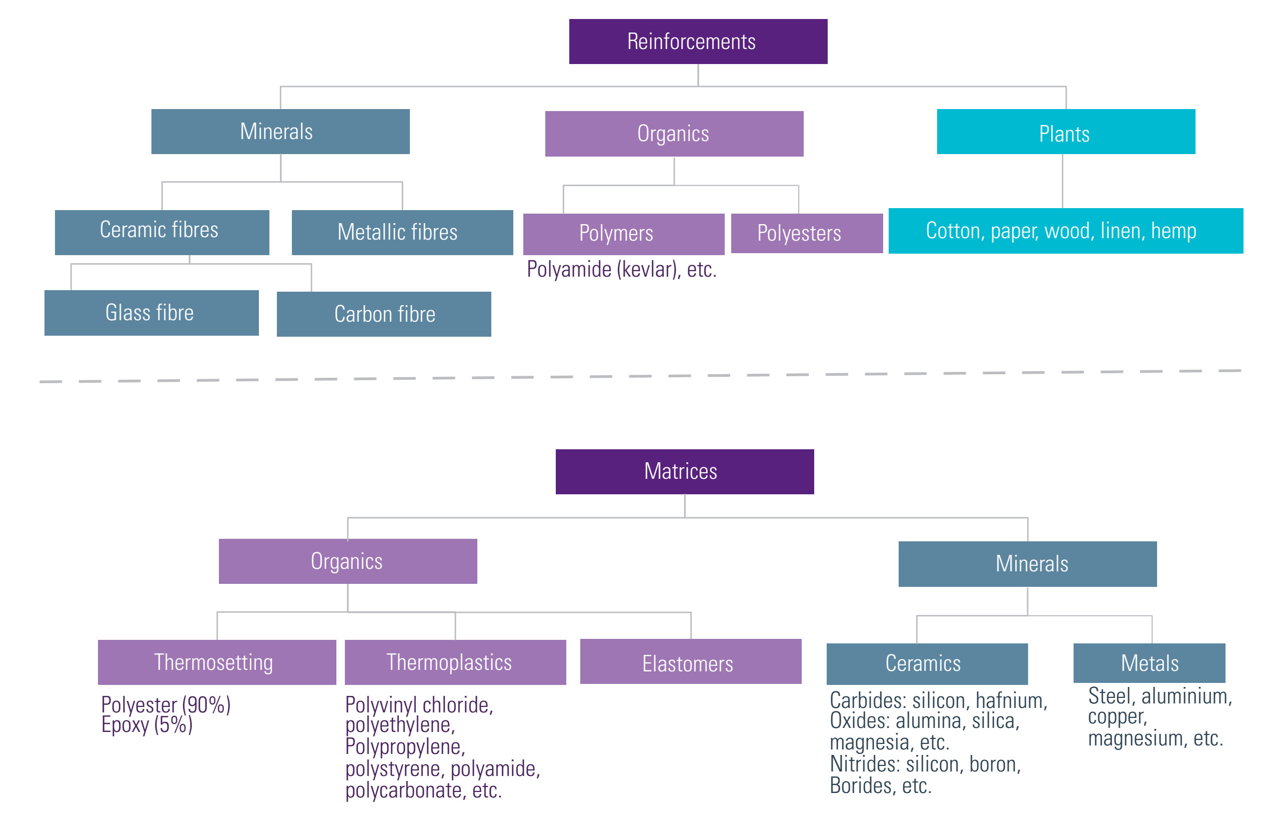
Fibreglass is the most popular reinforcement on the market (~95% market share). Fibreglass is widely used despite a relatively low mechanical performance because it is suitable for various applications and is inexpensive. Carbon fibre exhibits better mechanical behaviour, but at a less affordable price. Vegetable fibres, though renewable and inexpensive, are only used for less important parts. Finally, aramid (aromatic polyamide) fibres present high impact resistance, and are most widely used in the military industry, as ballistic protection.

Figure 51: Reinforcement characteristics

	Advantages	Disadvantages	Main applications
Glass fibre	Low cost (~1€/kg)	mediocre mechanical properties	'wide-scale distribution'
Carbon fibre	excellent mechanical properties	High cost (~21€/kg)	'high performance'
Polymer/ aramidic fibre E.g. kevlar	Good traction characteristics, high impact resistance	High cost (~20 €/kg), Low adhesion to matrices	Aerospace and armaments (ballistic protection, bulletproof vests)
Metal fibre	Stability of mechanical properties at high temperatures	High cost (1000 €/kg), Difficult to manufacture	Buildings
Vegetable fibre E.g. hemp, flax	Low cost of manufacturing	Weak mechanical properties	Shipbuilding, automotive and civil engineering industries

Sources: Mirova according to (Centre d'Animation Régional en Matériaux Avancés, 2004; ENS Mines de Paris (G.Cailletaud), 2012; Onera, 2011)

Figure 50: Constitution of a composite



Sources: Mirova, (Les Techniques de l'Ingénieur, 2011)

Given these factors, we may note that:

- The mechanical performance of fibreglass must be improved to make it usable and relevant to lightweight solutions
- Carbon fibre as a reinforcement offers the greatest potential to equal or exceed steel in terms of weight reduction. However, it remains expensive. R&D efforts should therefore focus on this point

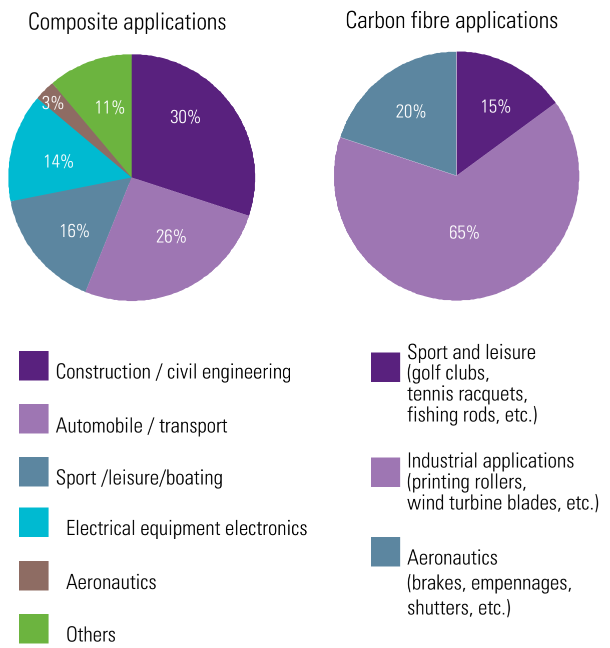
2. The composites market

a. Current production

In 2010, global production of composites was 8.6 million tonnes with an increase of 6% per year (JEC Composites, 2012). More specifically, the global production of carbon fibre was 48,690 tonnes (Société chimique de France, 2012) compared to 1.3 billion tonnes of steel and 4 to 5 million tonnes of fibreglass-reinforced composites (Roland Berger, 2012). Carbon fibre production is divided between the United States (33%), Japan (33%), Western Europe (25%) and Asia excluding Japan (9%).

Applications of carbon fibre are shown in the figure below.

Figure 52: Composite and carbon fibre applications (2011)



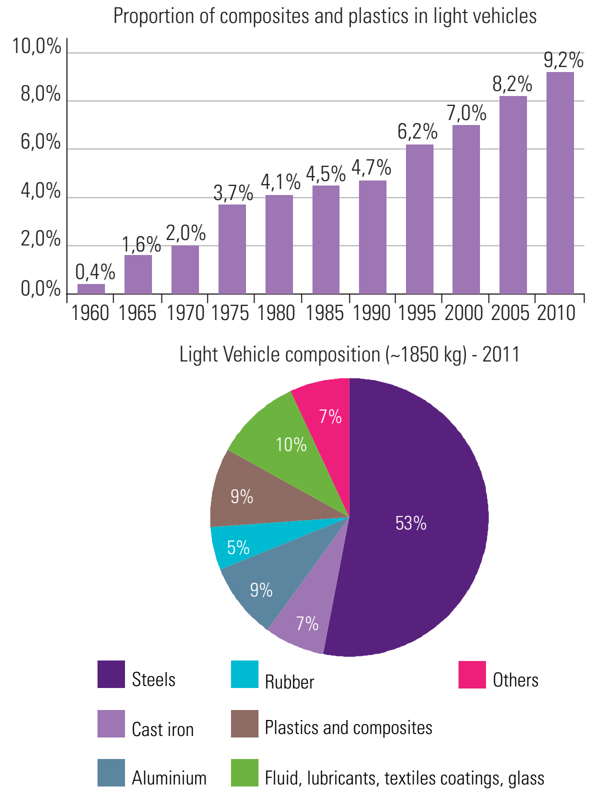
Sources: Mirova according to (Polytechnique de Montréal ; Pangaud, 2011 ; Cetim-Cermat, 2011)

b. Applications of composite reinforcements in mobility

1. Composites in the automotive industry

The automotive industry introduced composites into vehicles during the 1950s. Since the 70s, the penetration of composite materials has grown as shown in the figure below. At first, composites were thermoset, reinforced by short strand fibreglass (Sciences de l'Ingénieur, 2011).

Figure 53: Composites as a proportion of light vehicles since 1960



Sources: Mirova according to (Economics & Statistics Department American Chemistry Council, 2012)

Manufacturers have, in the past, chosen to integrate composite materials for various reasons: mechanical performance, technical specifications, space saving, etc. Here, we must distinguish carbon fibre reinforced composites used for weight reduction in place of steel from composites and plastics already in the vehicle. Thus, when the decision is made to use composites to make vehicles lighter, the composites need to have a large enough resistance to use in place of steel. However, the composites greater than or equal to steel in terms of mechanical performance are primarily those reinforced with carbon fibres, also known as carbon fibre reinforced plastic (CFRP). These can have a thermosetting or thermoplastic matrix reinforced by a minimum of carbon fibre, which may be accompanied by other reinforcements (aramid fibres, metallic fibres or fibreglass). At this juncture, such composites are almost nonexistent in currently offered vehicles. Only a few manufacturers in the premium segment have launched the massive investments needed to position themselves on this type of material (see section E.3 of this chapter).

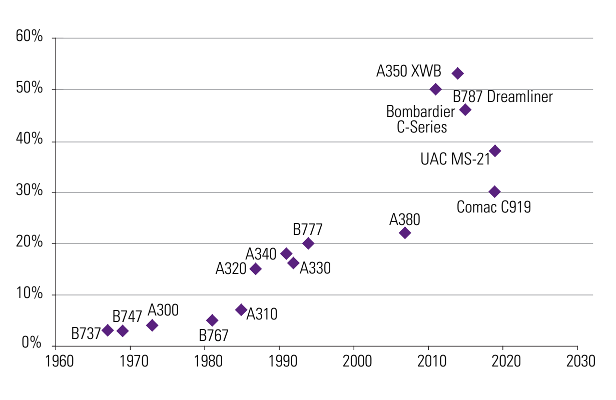
2. Composites in the aviation industry

Within the aviation industry, the development of CFRP has been rather different. Composites emerged there in the 60s. Initially, the composites used were organic resin reinforced with fiberglass for aircraft interiors (floors, fairings, cowlings). However, these first composites lacked rigidity.

In 1970, carbon fibre was introduced in some components such as pods, the moving parts of wing spoilers, support rods, etc. In 1972, the ATR 72 (capacity 70) became the first civilian aircraft to comprise CFRPs, with a series of wing boxes made of carbon fibre (Noetinger, 2005). Aramid fibre has since been incorporated into fairings (Les Techniques de l'Ingénieur, 2011).

There are several reasons for the use of composites in aerospace: weight reduction, fatigue resistance and corrosion resistance. Aircraft would weigh 30% more were they still built using conventional metallic materials (Presses Polytechniques et universitaires romandes, 2004).
Today, long-haul aircraft can be made up of upto 50% composites (B787 Dreamliner and A640 XWB).

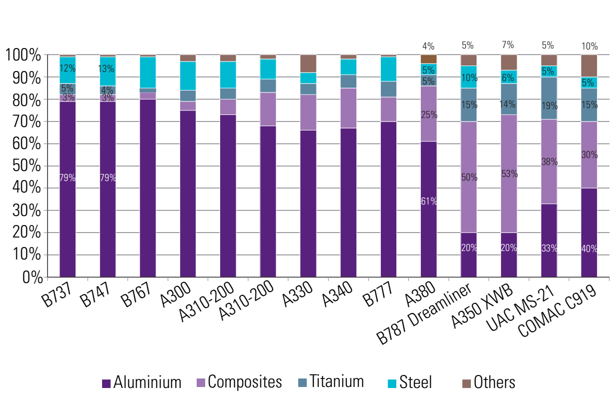
Figure 54: Percentage of a plane comprised of composites since 1960



Sources: Mirova according to (Airbus; Boeing; Les Techniques de l'Ingénieur, 2011)

Of course, weight is not the only issue facing the airline industry. Reducing an aircraft's CO_2 emissions involves a mixture of factors: 50% improved engine, 30% structure and 20% air-traffic control organisation and structure (Easyjet plc, 2007). Nonetheless, the weight reduction argument has encouraged a substitution of aluminium with CFRP, as shown in Figure 56.

Figure 55: Changes to the distribution of materials used in planes



Sources: Mirova according to (Airbus; Berger, 2012; Boeing; Missouri University of Science and Technology)

In aerospace, mechanical properties are extremely important for maintaining strength at lower weights. In civil aviation, the composites employed are largely 'high performance' organic matrix composites. In the majority of cases, the thermosetting matrix (epoxy) is reinforced with carbon fibre. However, the industry is now more interested in the thermoplastic matrix, which, unlike thermosetting matrices, can be recycled almost indefinitely.

Manufacturers of both the A350 XWB and Boeing 787 Dreamliner models, which are made of more than 50% composite materials, are also studying the potential for incorporating CFRP on a larger scale than ever before. The passenger door of the A350 XWB, designed by Eurocopter, is 100% CFRP. Like BMW in the automotive industry, whose i3 and i8 models are already scheduled for production (see Insert 5), these manufacturers are working toward an expanded role for CFRPs.

3. Keys to the development of composites

a. Changes in carbon fibre precursors

Thomas Edison first developed carbon fibre in 1880, when he used bamboo fibre to make a light bulb. In 1957, the Barnebey-Cheney Company, the National Carbon Company and Carbone Lorraine reinvented carbon fibre using rayon. And finally, in 1961, the latest developments in fibre were made using polyacrylonitrile (PAN) by Shindo, part of the Osaka Industrial Research Industry in Japan. This progress has made possible 'high performance' materials with a tensile strength of 1500 MPa and a tensile modulus of 150 GPa (Gigapascals). Meanwhile, in 1964, the University of Gunmar in Japan, and CERCHAR in France between 1969 and 1972, managed to obtain carbon fibres using pitch fibres derived from coal and petroleum (Techniques de l'Ingénieur, 1993). Later, much progress was made in terms of PAN-based carbon fibres by various manufacturers: Union Carbide (USA), Morgan Crucible (UK), Rolls Royce (UK), Courtaulds (UK), Nippon Carbon (Japan) Tokai (Japan), Toray Industries (Japan), Hercules (USA), Carbone Lorraine (France), Rhone-Poulenc (France) and Toho Beslon/Rayon (Japan).

At present, there are three potential precursors: rayon, pitch and polyacrynolitrile (PAN). However, rayon and pitch-based carbon fibres have since almost disappeared: rayon for want of competitiveness and poor mechanical performance, pitch because of complex implementation and uneven quality combined with limited tensile strength. Thus, we will only be discussing PAN-based carbon fibres.

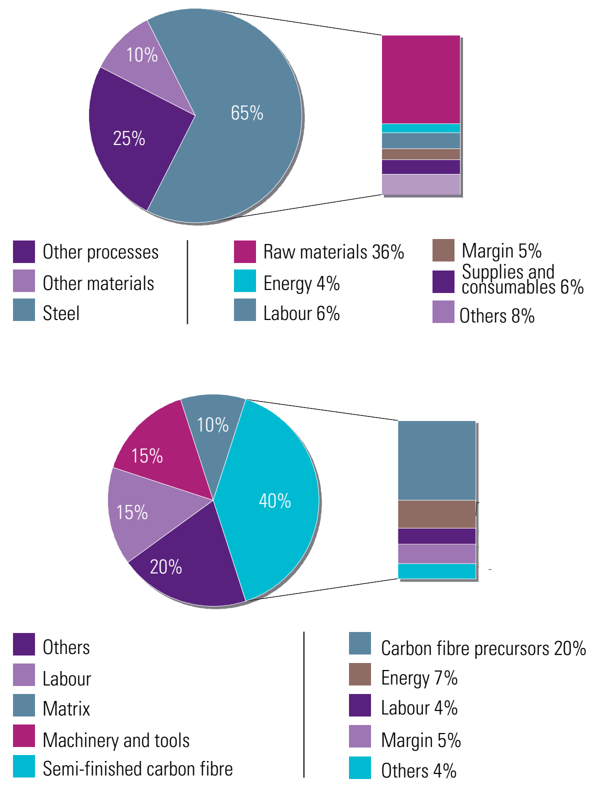
b. Barriers to development for composites

The major development barrier for carbon fibre composites is cost. In addition, there are also difficulties in terms of maintenance, recycling and cycle time.

1. Cost

The diagrams below compare the cost structures of carbon fibre composites and steel composites for a component measuring 0.8 m x 0.8 m and weighing 1.8 kg at a cost of between €50 and €60 for the former, against a weight of 4.5 kg for a cost of ~ €10 for the latter.

Figure 56: Cost structure of carbon-fibre reinforced plastics vs steel sheet



Sources: Mirova according to (Roland Berger, 2012, Science and Technology)

As we can see in the figures above, 40% of the cost of a carbon fibre reinforced composite (CRFC) is due to its reinforcement (the carbon fibre) and more specifically 20% to precursors. However, in contrast to steel, raw materials do not make up a large part of its cost: ~ 75% raw materials and ~ 25% processed for steel vs. ~ 50% raw materials and ~ 50% process for CFRPs.

The carbon fibre industry therefore needs to make significant advances with regards to raw materials as well as the manufacturing process.

2. Maintenance

Repairing composite carbon fibre is problematic because damage is in many cases invisible. Detecting internal faults may require the use of acoustic emissions, thermal imaging or ultrasound. Repair methods developed for aerospace and, depending on the damage, may be applicable to the automobile sector. However, there is little understanding or consensus on how to resist ageing and corrosion. In short, the maintenance obstacles of carbon fibre are not insurmountable, but do add to the investment costs.

3. Recycling

Since 2006 under EU law, materials for reuse or recovery at end-of-life must represent 85% of the average weight of a new vehicle; this will increase to 95% as of January first 2015 (Europa, 2011). Regulation hinders the use of carbon fibre here for two reasons:

- ➜ Given that composites and carbon fibre are a mixture of compounds, they are by definition more complex to recycle
- ➜ Manufacturers aren't encouraged to use carbon fibre, indeed they have an interest in recycling other more impressive and heavy parts of vehicles than in using carbon fibre to conform with regulations

At this stage, 90% of thermosetting matrix composite waste is landfilled (Cetim-Cermat, 2011). To ensure the presence of carbon fibre within the automotive sector, technological advances must be made with regards to recycling

4. Cycle time

Given a production output in the automotive industry (world production of 63 million vehicles in 2012 i.e. 120 vehicles/minute), the cycle time for CFRP must be shortened if it is to compete. In 2011, this cycle time was about 15 to 20 minutes (Sora Composites, 2011).To incorporate this material as the production process stands, manufacturers need multiple presses and several moulds for composites to keep pace with all other parts. This equipment would result in increases to other costs, a difficult notion to accept in the automobile sector, which is already very restricted by price considerations. Thus cycle time is a major barrier for composite materials and plastics (Duval, 2007) in the jump from supercars to other types of vehicles.

c. Solutions throughout the value chain

The value chain of CFRP includes two main steps (Dupupet, 2008):

1) Transforming acrylonitrile monomers into polyacrylonitrile fibres (PAN) via polymerisation, spinning/coagulation, finishing and winding treatment (Toray Carbon Fibers Europe, 2013)

2) Transforming PAN fibres into carbon fibres: air oxidation at 200°C or 300°C, carbonisation under internal gas at 700°C or 1,500°C, graphitisation under internal gas at 2,000°C or 3,000°C, surface treatment (to treat the interface between the fibre and the matrix) and warping

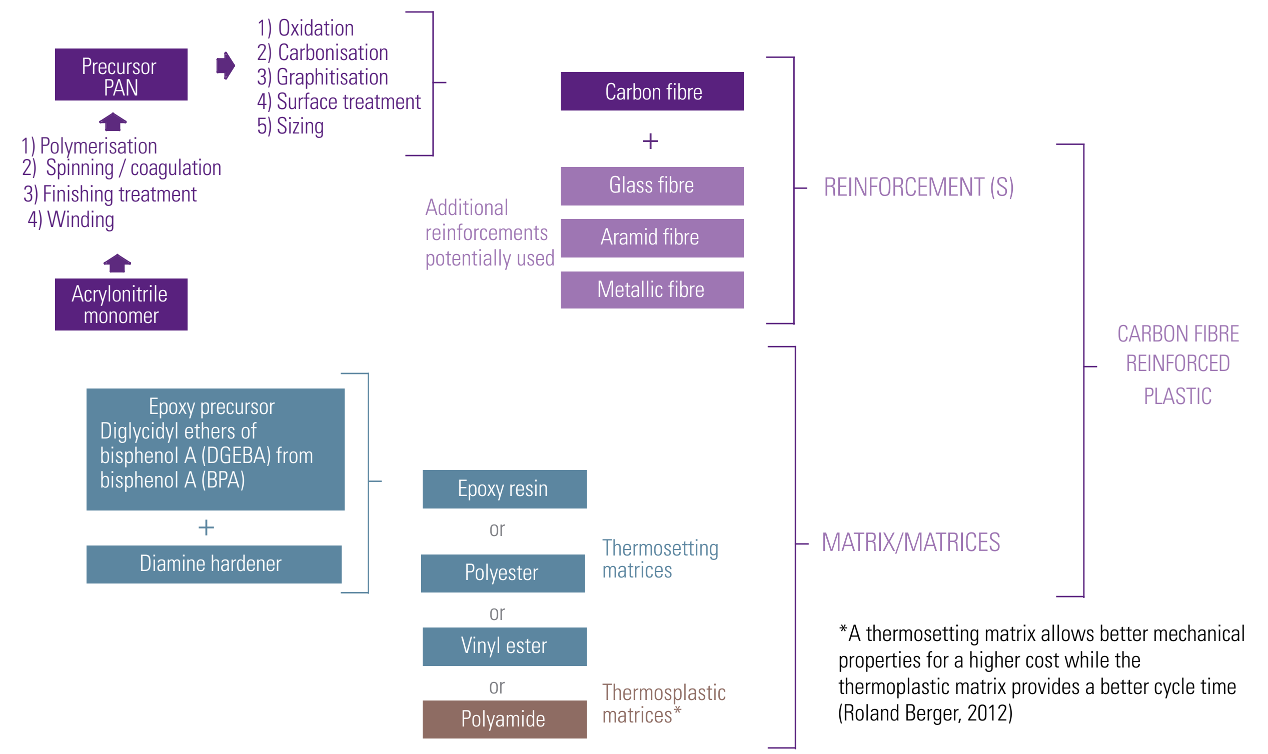
1. A potential cost reduction of at least 30% by 2020

Two technological processes are being developed to reduce costs (Berger, 2012; Kozarsky, 2012; U.S Departement of Energy, 2012):

1) Atmospheric pressure plasma oxidation (PO) (reduces cost by half compared to conventional oxidation)

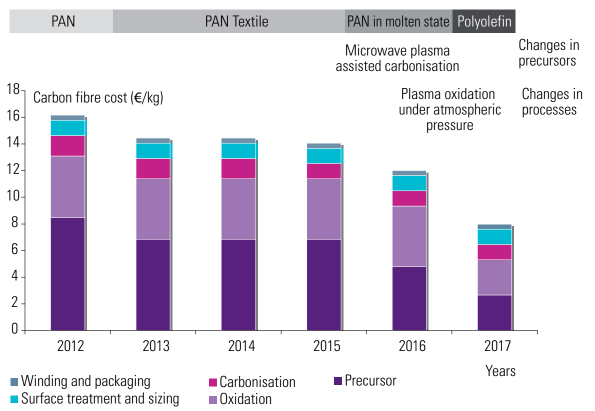
2) Microwave-assisted plasma carbonisation (MAP) (reduces cost by 25% compared to conventional carbonisation)

Figure 57: Process for producing carbon-fibre reinforced composites



Source: Mirova according to (Sylvain Caillol, 2011), (Luyckx, 1992)

Figure 58: Contribution of processing to global cost of carbon fibre by phase



Source: Mirova according to (Kozarsky, 2012; US Department of Energy, 2012)

For raw materials, research is underway to find alternatives for traditional PAN precursors. In the short term, the PAN precursor will be replaced by a chemically modified PAN textile (cost reduction between 20% and 25%), medium-term PAN melt (cost reduction of more than 25%) or polyolefin (> 50%) and in the longer term, lignin will provide cost reductions of up to 70% (Berger, 2012; Kozarsky, 2012; US Department of Energy, 2012).

Taken together, these technological advances could permit a reduction of 25% (Berger, 2012) to 50% (US Department of Energy, 2012) in the cost of carbon fibre. The penetration of carbon fibre in the car sector could then be dramatically accelerated, as shown in the figure below.

Figure 59: Estimated automaker demand for carbon fibre steel substitutes by 2017

Vehicle type	Estimated production in 2017	Estimated carbon fibre use in cars	Demand for carbon fibre (kg)
Supercars	6 000	100%	590 000
Super luxury vehicles	600 000	10%	46 000 000
Luxury vehicles	4 000 000	10%	46 000 000
Medium vehicles	92 000 000	1%	92 000 000
Global automobile production	96 606 000		184 590 000

Source: Mirova according to (US Department of Energy, 2012)

It is worth noting potential cost reductions coming from the matrix material (less than 10%) and production methods, notably through optimisation and automation processes (around 30 to 40%). Thus, according to estimates by the US Department of Energy and Roland Berger, the total potential cost of carbon fibre reinforced composites, currently ~50 €/kg, could drop to ~30/35 €/kg by 2020.

2. 'Carbon fibre recycling' is now possible

As indicated in the section on composites, only thermoplastic matrices are reusable and recyclable. Nevertheless, research is underway to process thermosetting matrices and partially reuse them (Boutin & Laisney, 2005).

Leaving aside the thermosetting matrix, it is possible to recover cutting and shaping waste (~30% of all carbon fibre used) for applications requiring less strength or size. In addition, two methods have been developed to improve carbon fibre recycling (McKinsey & Company, 2012): crushing and thermal/chemical cracking (recycled carbon fibre has a lower mechanical performance, but may be reused). In December 2012, Boeing and BMW signed a research partnership to investigate the recycling of carbon fibre (BMW Group, 2012). Their involvement and investment improves the outlook for this technology.

3. Cycle time may transform automakers' business model

Since 2011 (Teijin, 2011), Teijin has provided technology for mass production of CFRP with a cycle time of one minute to produce a passenger compartment (Teijin, 2012). Similarly, Ford has produced the prototype of a Ford Focus with a bonnet made of carbon fibre, and aims to produce it on a small scale as a test with a target overall cycle time of 15 minutes. To achieve this, Ford worked with Toho Tenax[9] (carbon fibre), Henkel[10] (thermosetting matrix), Rohacell d'Evonik[11] (foam core), IKV[12] and Composite Impulse (Ford, 2012). Many current partnerships and investments are dedicated to improving cycle times. These involve automanufacturers, carbon fibre producers, chemical companies such as Zoltek (Zoltek, 2013), Plasan Carbon Composites (Composites World, 2013), Momentive, BMW, SGL Carbon, Dow Chemical (Composites World, 2012), etc. At this stage, we cannot guarantee that technical progress will ensure CFRP equipped cars under the current automotive production model. However, the appearance of CFRPs in vehicules coincides with changes to vehicule use in urban contexts. For instance, electric vehicles have already altered transportation in many cities: use of a vehicle is charged for depending on distance travelled, leading to a new business model anchored in the service economy (see Insert 4 below).

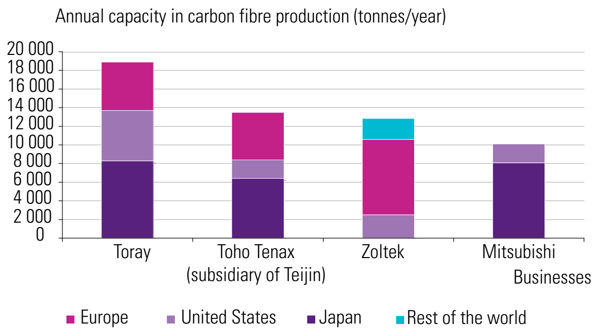
d. A wealth of opportunities for companies able to meet demand

Given that current production of carbon fibre is less than 50,000 tonnes, technological advances and rising demand could create a turning point for firms in the carbon fibre and lightweight vehicles sector.

Production capacity has heretofore always been slightly above demand, except during periods of crisis. Figure 60 shows the production capacities of dominant producers.

9. More information: http://www.tohotenax.com/tenax/en/products/pro_carbon01.php
10. More information: http://www.henkelna.com/adhesives/product-search-1554.htm?primaryFacet=00000002MQ#
11. More information: http://www.rohacell.com/product/rohacell/en/about/pages/default.aspx
12. More information: http://www.compositesworld.com/news/ikv-develops-gap-impregnation-molding-system-for-polyurethanes

Figure 60: Annual carbon-fibre production capacity (tonnes/year) in 2010



Source: Mirova according to (Société chimique de France, 2012)

In addition to the companies listed in the chart, other companies are present in this market such as Citex (USA), Hexcel (USA), SGL Group (Germany), Ordos Yaxin Carbon fibre (China), Aksa (Turkey), Kuhera (Japan), Soficar (France), Plasan Carbon Composites (USA) and Sora Composites (France), whose automotive business Faurecia acquired in 2012 (Faurecia, 2012), etc.

Aksa Akrilik Kimya Sanayii has created a joint venture with Dow for a USD 1 billion investment project, while BMW and SGL Carbon signed a €230 million investment partnership in 2009 (Les transports du futur, 2012).

Car manufacturers such as BMW and Tesla Motors, who have until now been the most invested in CFRP, will also benefit from advances in technology. However, two approaches to composite materials and their integration into the automobile world must nevertheless be accepted here (See inserts 4 and 5).

Finally, certain chemical companies, such as BASF, Dow, etc. are also positioned to benefit from these opportunities.

Figure 61: Main carbon-fibre development partnerships in the automotive industry

Manufacturers	Partners	Vehicle (vehicle part concerned)
BMW	SGL Carbon (fibre)	i3 and i8 (structure)
Lamborghini	Advanced Composite Research Centre	Aventador LP 700-4 (chassis)
Volkswagen	SGL Carbon	XL1 (bodywork)
Tesla Motors	Sora Composites	Roadster (bodywork), Model S (spoiler),
Ford	Toho Tenax	Focus (bonnet)
Toyota	-	Lexus LFA (tub)
Audi	Voith	Upcoming
Daimler	Toray	Mercedes E Class Superlight (upcoming)
General Motors	Teijin	Chevrolet Corvette (upcoming)

Source: Mirova according to company reports

Insert 4: What if the vehicle business model were to change with the arrival of composite materials?

Exchanges with Steve Evans, Director of Research in Industrial Sustainability, Institute for Manufacturing and partner at Riversimple (http://www.riversimple.com/Default.aspx)

Riversimple is a company that seeks to meet various stakeholders' expectations by offering:

- A fuel cell vehicle with a carbon fibre composite single hull (to create the lightest vehicle possible through the use of carbon fibre to reduce demand on the engine)
- A mobility service (monthly rental charge + charge per mile travelled) and not a mobility product (this allows the lightweight aspect to be seen as an opportunity for the client to lower their hydrogen costs per month)

This offer has led to a change in business model, which Riversimple deems essential before carbon fibre can enter the automobile market. The greatest barrier to carbon fibre is the perception that it is difficult. Investments in steel and aluminium are recouped through massive sales, while carbon fibre, because of its long cycle time, is limited to small-scale production.

Moreover, the integration of carbon fibre is currently achieved mainly using carbon fibre panels positioned as steel panels. In the long term, structures designed to the specific properties of carbon fibre will optimise the mechanical properties of the fibre and its lightweight capabilities (as is currently the case with electric vehicles specifically designed for this propulsion mode).

These technological breakthroughs demand substantial investment from car manufacturers, who are already experiencing cost cuts which limit flexibility. For these reasons, a different business model seems essential for the integration of carbon fibre vehicles, according to Riversimple.

Riversimple aims to market a product that consumes 1 litre per 100 km, with an average speed of 80 km/h, an overall weight of 390 kg and a battery life of 380 km.

Insert 5: Carbon fibre on an industrial scale can be an option

Exchanges with Carina Wollmann, Investor Relations at BMW following innovation days organised by the group in April 2013.

Although Riversimple's philosophy (see Insert 4 above) is based on objective findings, BMW suggests that CFRP can be used for mass production. In 2013 and 2014, the German automaker will put into large scale production two models with a CFRP body: the 'i3' an electric vehicle or range extended electric vehicle version and the 'i8' a plug-in hybrid vehicle with a range of 35 km in pure electric mode. The 'i3' has a range of 160 km. To optimise the vehicle's performance and extend its range, the design has been completely revamped (lowering the centre of gravity, specific location of the battery in the floor, etc.).

In order to achieve this kind of production with CFRP and launch its 'i' strategy, the group has set up a parallel production line that has been completely redefined compared with conventional vehicles. For example, this new production process does not include press shops (pressing is useless with CFRP) and paint shops (CFRP are already colored) which can help reduce production costs. Instead, new processes have been implemented in partnership with SGL Carbon. Thanks to the elimination of unnecessary production stages and improved curing techniques/collage, BMW has managed to significantly reduce cycle time. The group uses renewable energy to produce carbon fibre reinforced composites that reduce the carbon footprint of the material over its entire life cycle and capture a CO_{2eq} 50% lower compared to the production of classic CFRP. At Moses Lake (USA), hydroelectric power is used to manufacture carbon fibres using polyacrylonitrile as a precursor. Then, production continues at the Wackersdorf site, where fibres are structured to optimise mechanical properties, and in Landshut or Leipzig to obtain the final composite. 100% of the energy used comes from wind in Leipzig (turbines installed on factory grounds). By using renewable energy and improving the energy efficiency of production, BMW is able to offer vehicles with a global warming potential reduced by 30% compared to traditional combustion vehicles using an EU electricity mix and 50% with renewable energy.

Thanks to roughly ten years of experience in the production of CFRPs, BMW has reduced the cost and cycle time for a component of equivalent dimensions (e.g. the roof) by 50% and 30% respectively. BMW manages the entire value chain for the 'i' models and thus widens the technological gap with its competitors by its use of proprietary processes. Moreover, this in-house production model permits BMW to experiment with recycling carbon fibre from production waste. Approximately 10% of carbon fibres are made up of former waste fibre.

Finally, BMW has developed specific methods for repairing this type of model to guarantee its customers that repair costs do not exceed those of a BMW 1 series. The company will build specific repair centres to this effect. Like other vehicles in the group, the new 'i' vehicles are tested to ensure theycomply with the most stringent regulatory requirements.

F. Other examples of promising lightweight materials

1. Titanium for niche opportunities

Approximately 6% of titanium production is used for titanium metal, the rest is employed in paint or pigments. Titanium metal is made from the production of titanium sponge, which in most cases is based on the energy intensive Kroll process that requires substantial industrial installations (Association Française du Titane, 2011). Global production in 2010 was 100,000 tonnes (Société chimique de France, 2012) which is low in comparison to other lightweight metals (45 million tonnes of aluminium and 800,000 tonnes of magnesium in 2011). This limited production is explained by the high cost of the production process and a relatively low total production capacity of 283,000 tonnes in 2012 (which still exceeds the current demand). The main producers are: Osaka Titanium Technologies Co. in Japan, VSMPO-AVISMA in Russia, Titanium Metals Corp Allegheny Technologies Inc. and Honeywell Electronics Materials Inc. in the United States, Ust-Kamenogorsk Titanium-Magnesium Complex in Kazakhstan and Zaporozhye Titanium and Magnesium Combine in the Ukraine (Société chimique de France, 2012). The graph below indicates that titanium has historically been more expensive than magnesium or aluminium.

Recycling of titanium is very important, because it permits the recovery of chips inevitable in the machining of titanium metal. Recycled titanium is then used to produce titanium ingots or ferro-alloys (titanium alloys and aluminium used for steel construction and stainless steel alloys). In 2012, 35,000 tonnes were recycled (USGS, 2013).

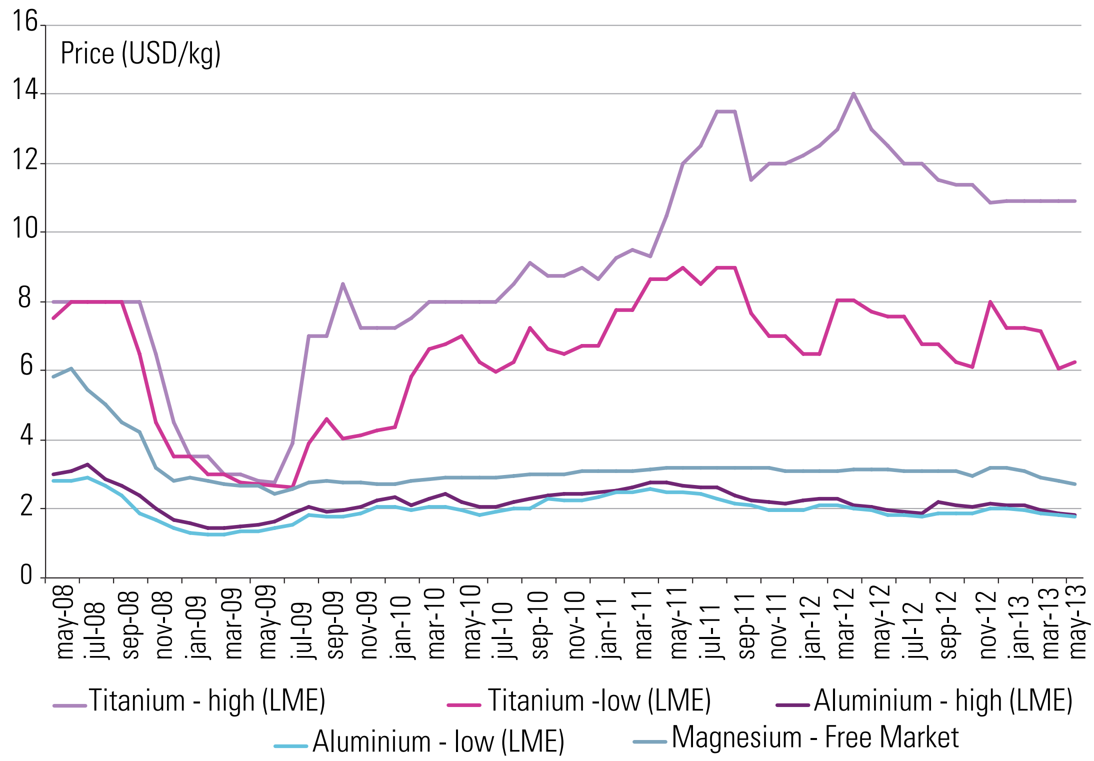
Titanium is identified as a potential lightweight material to replace steel thanks to its mechanical performance (excellent potential weight/resistance) and corrosion resistance. Demand is mainly driven by civil aviation, which represented 43% of demand in 2008. According to the French Titanium Association, this demand is expected to increase by 2020 with the arrival of the A350 and the 787 Dreamliner planes in which titanium constitutes about 15% of each plane's weight. More generally, the use of titanium in civil aviation has increased since the 70s, its presence in aircraft moving from 5% to 15% (pipes, engine parts, landing gear, internal components). While widely used in aerospace, titanium is limited in the automotive industry to niche applications for high-end vehicles or Formula 1.

As technological innovation indicates no hope for producing titanium metal from a process less energy consuming or expensive than the Kroll process, titanium will not be a key priority for the car industry.

2. Graphene as a promising material

A product of graphite, graphene is a carbon atom. In 2004, Andre Geim and Konstantin Novoselov (now Nobel laureates for this discovery) succeeded in isolating graphene sheets and positioned graphene as a material with potential for lightweighting. Indeed, 1% graphene mixed into plastics would provide a mechanical strength 200 times higher than that of steel in terms of tensile strength. The demand for graphene could reach USD 20 million by 2020 for use in composites (Lux Research, 2013), however this material is currently only at the R&D stage.

Figure 62: Price variations of aluminium, magnesium and titanium, May 2008 to May 2013



Source: Mirova according to (Les Echos, 2013) (InfoMine, 2013)

4 | Conclusions

The study above contributes to the literature of environmental science, industrial development and applied economics in several different ways. First, it cogently argues that lightweighting of vehicles presents gains in required useful energy that have desirable repercussions upstream such that the actual benefit is in fact larger than the direct advantage alone. This makes lightweighting a priority of the highest importance. Second, it offers a unique horizontal analysis of the current state of research and development across almost all the material solutions envisaged for lightweighting in the automotive industry at this time; indeed, one limitation of many previous studies is that they investigate a single material or area of lightweighting (motor, chassis, etc.). The work presented here also compares these materials on the basis of a life cycle analysis (LCA) which allows for a better overall comprehension of their relative positions within efforts to limit climate change and reduce negative environmental outcomes in general. By tracing the entire value chain, the study is able to expose and compare hidden risks as well as both economic and environmental opportunities not visible at the level of the end-product (i.e. cars). The parallel consideration of challenges and risks facing the use of each material further clarifies the constellation of issues surrounding weight in the automotive industry from both a theoretical perspective and in terms of insights applicable to investment decisions.

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